Holistic Aeropropulsion Concepts

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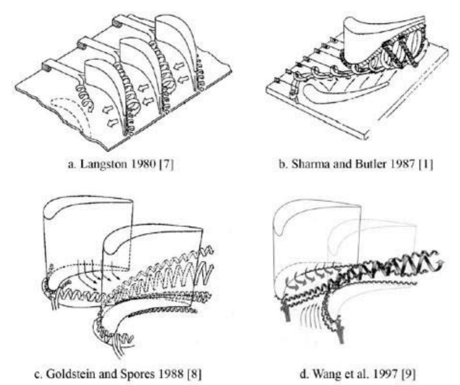

Fig. 1.5 Secondary flow field models from a. Langston [7], b. Sharma and Butler [1], Goldstein and Spores [8], and Wang et al. [9].

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Christopher Snyder – GRC/RTM
Surya Raghu – Advanced Fluidics LLC
Mike Zelek – GRC/FTC
Adam Wroblewski – GRC/RHI

Figure 3: Prepared bird wings used for the presentation of the results

NASA Aeronautics Research Mission Directorate (ARMD)

2014 Seedling Technical Seminar

February 19–27, 2014

Outline

- **Motivation**
- Background
- Objectives
- Approach
  - Biomimicry
  - Autonomous Closed-Loop Flow Control (ACFC)
- Results
- Conclusions

NASA Aeronautics Programs

Fundamental Aeronautics Program

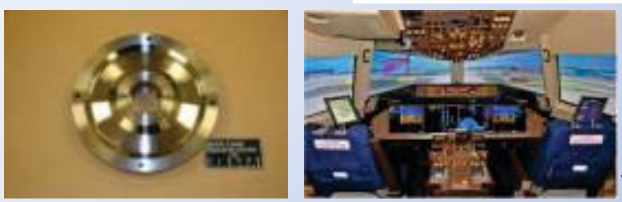
Conduct fundamental research that will produce innovative concepts, tools, and technologies to enable revolutionary changes for vehicles that fly in all speed regimes.

Integrated Systems Research Program

Conduct research at an integrated system-level on promising concepts and technologies and explore/assess/demonstrate the benefits in a relevant environment

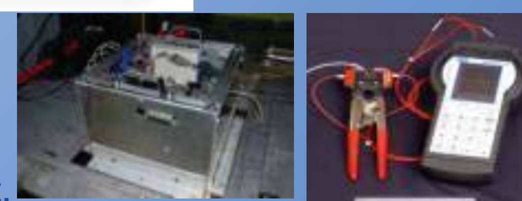
Airspace Systems Program

Directly address the fundamental ATM research needs for NextGen by developing revolutionary concepts, capabilities, and technologies that will enable significant increases in the capacity, efficiency and flexibility of the NAS.



Aviation Safety Program

Conduct cutting-edge research that will produce innovative concepts, tools, and technologies to improve the intrinsic safety attributes of current and future aircraft.



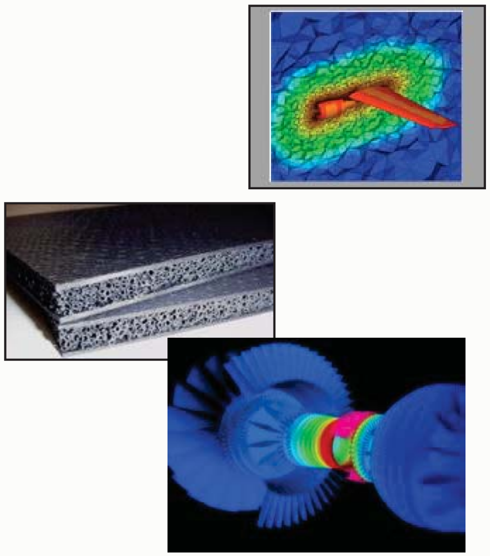
Aeronautics Test Program

Preserve and promote the testing capabilities of one of the United States' largest, most versatile and comprehensive set of flight and ground-based research facilities.

FA Program Organization Structure

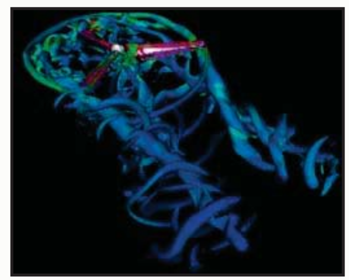
Fundamental Aeronautics Program Office

Aeronautical Sciences Project

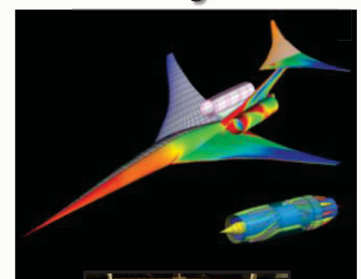


Fixed Wing Project

Rotary Wing Project



High Speed Project



Aeronautical Sciences (AS)
Enable fast, efficient design & analysis of advanced aviation systems from first principles through physics-based tools, methods, & cross-cutting technologies.

Fixed Wing (FW)
Explore & develop technologies and concepts for improved energy efficiency & environmental compatibility of fixed wing, subsonic transports

Rotary Wing (RW)
Enable enable radical changes in the transportation system through advanced rotary wing vehicles concepts & capabilities.

High Speed (HS)
Enable tools &technologies and validation capabilities necessary to overcome environmental & performance barriers to practical civil supersonic airliners.

NASA Subsonic Transport System Level Metrics

…. technology for dramatically improving noise, emissions, & performance

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TECHNOLOGY BENEFITS*	TECHNOLOGY GENERATIONS (Technology Readiness Level = 4-6)		
	N+1 (2015)	N+2 (2020**)	N+3 (2025)
Noise (cum margin rel. to Stage 4)	-32 dB	-42 dB	-71 dB
LTO NOx Emissions (rel. to CAEP 6)	-60%	-75%	-80%
Cruise NOx Emissions (rel. to 2005 best in class)	-55%	-70%	-80%
Aircraft Fuel/Energy Consumption‡ (rel. to 2005 best in class)	-33%	-50%	-60%

* Projected benefits once technologies are matured and implemented by industry. Benefits vary by vehicle size and mission. N+1 and N+3 values are referenced to a 737-800 with CFM56-7B engines, N+2 values are referenced to a 777-200 with GE90 engines

** ERA's time-phased approach includes advancing "long-pole" technologies to TRL 6 by 2015

‡ CO_2 emission benefits dependent on life-cycle CO_{2e} per MJ for fuel and/or energy source used

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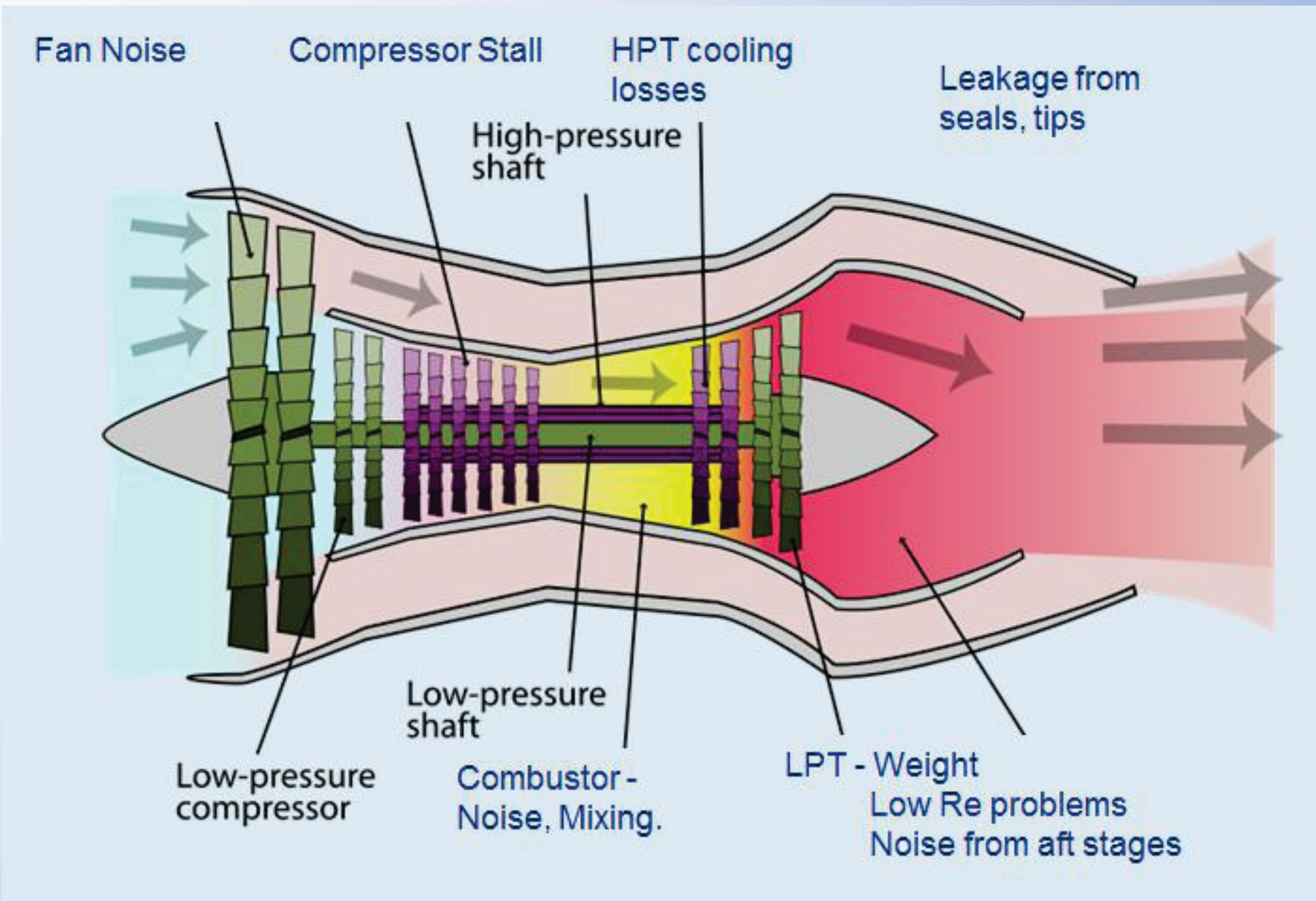
Sources of Performance Hits



http://en.wikipedia.org/wiki/File:Turbofan_operation_lbp.svg

Incidence, Low Re Problems

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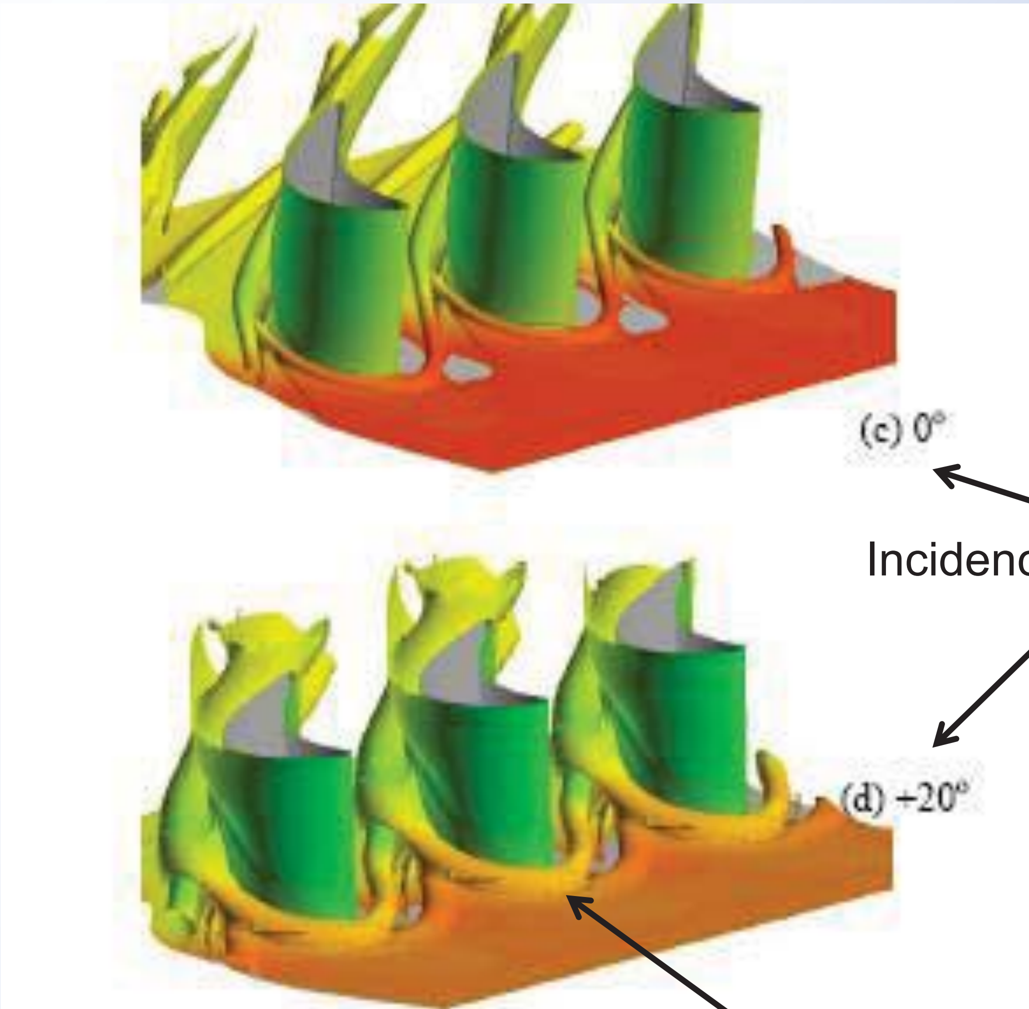
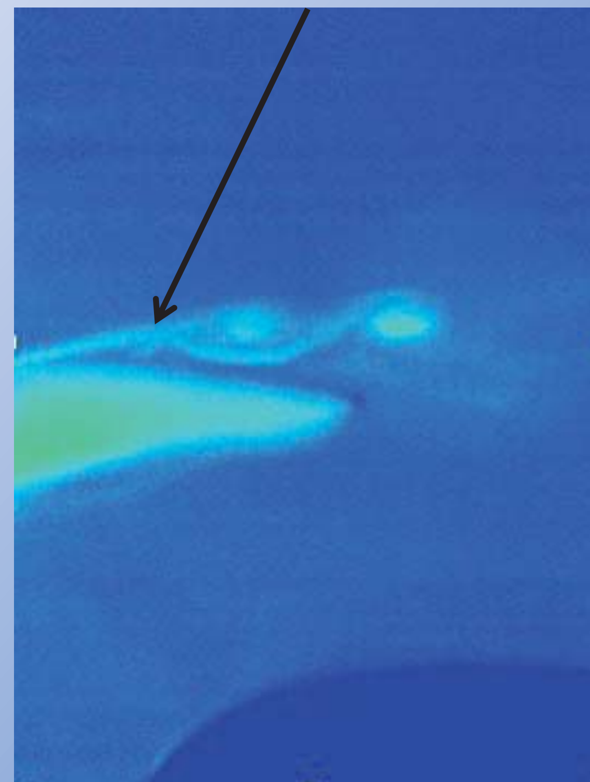


Incidence angle

Horseshoe vortex

Separation due to adverse pressure



Flow Control

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- Flow control attempted
  - Requires power
  - Local effects that could be detrimental elsewhere
  - Cannot adjust to changing environment
  - VGJs extensively researched
  - Blowing into BL is common
- Design compromise by averaging over mission
- Noise reduction by blowing into wake costs 5% compressor bleed – unacceptable
- Sensing of flowfield and thermal field requires sensors/power – trades performance for weight and cost

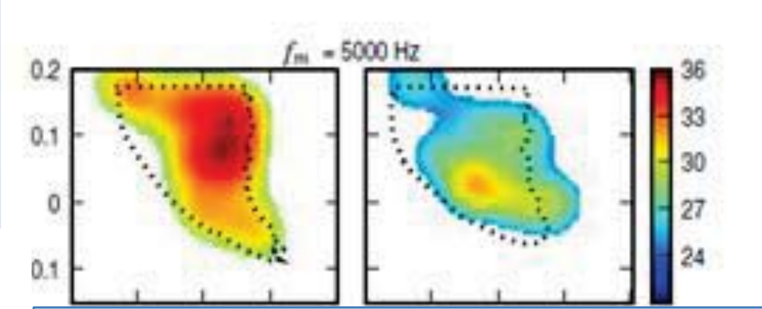
Biomimicry

- Imitating Life
- Using natural multi-parameter multi-objective optimization to solve aeropropulsion challenges
  - Get something for almost nothing
- Challenges
  - Geometric/ fluid dynamic scaling
  - Identifying relevant physics to incorporate

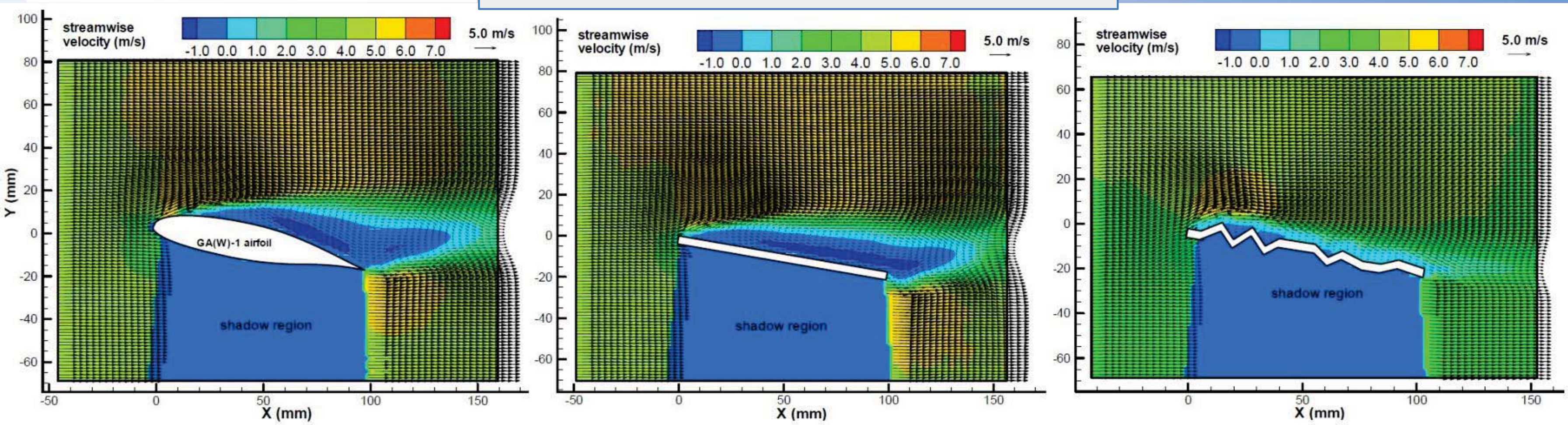
Known Bio-inspired Solutions

NASA Aeronautics Research Institute

Fish et al., “The Tubercles on Humpback Whales’ Flippers: Application of Bio-Inspired Technology” .

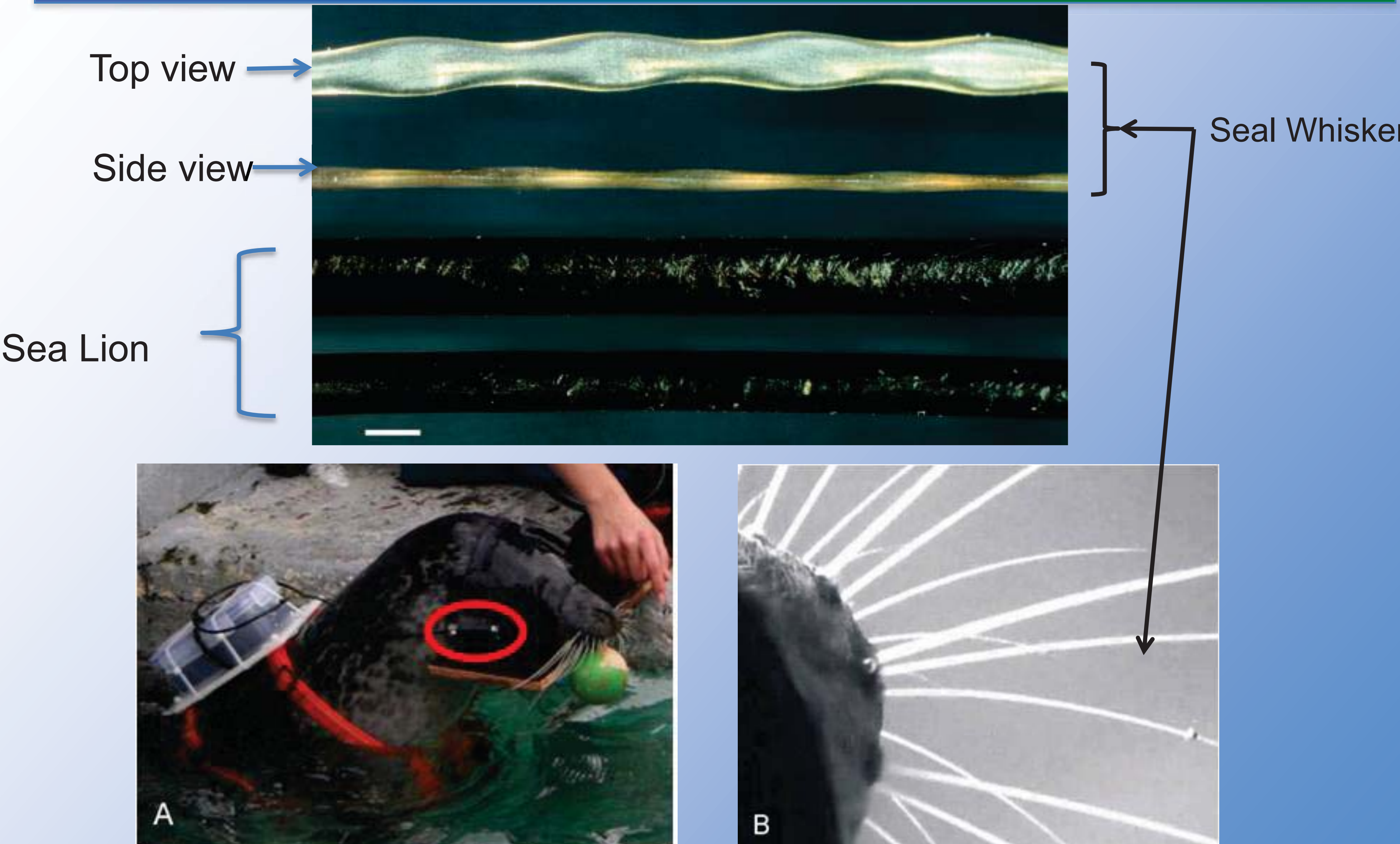


Geyer et al., “Silent Owl Flight, Experiments in the Aeroacoustic Wind Tunnel”



Tamai et al., “Aerodynamic Performance of a Corrugated Dragonfly Airfoil Compared with Smooth Airfoils at Low Reynolds Numbers”

Harbor Seal



Harbor Seal

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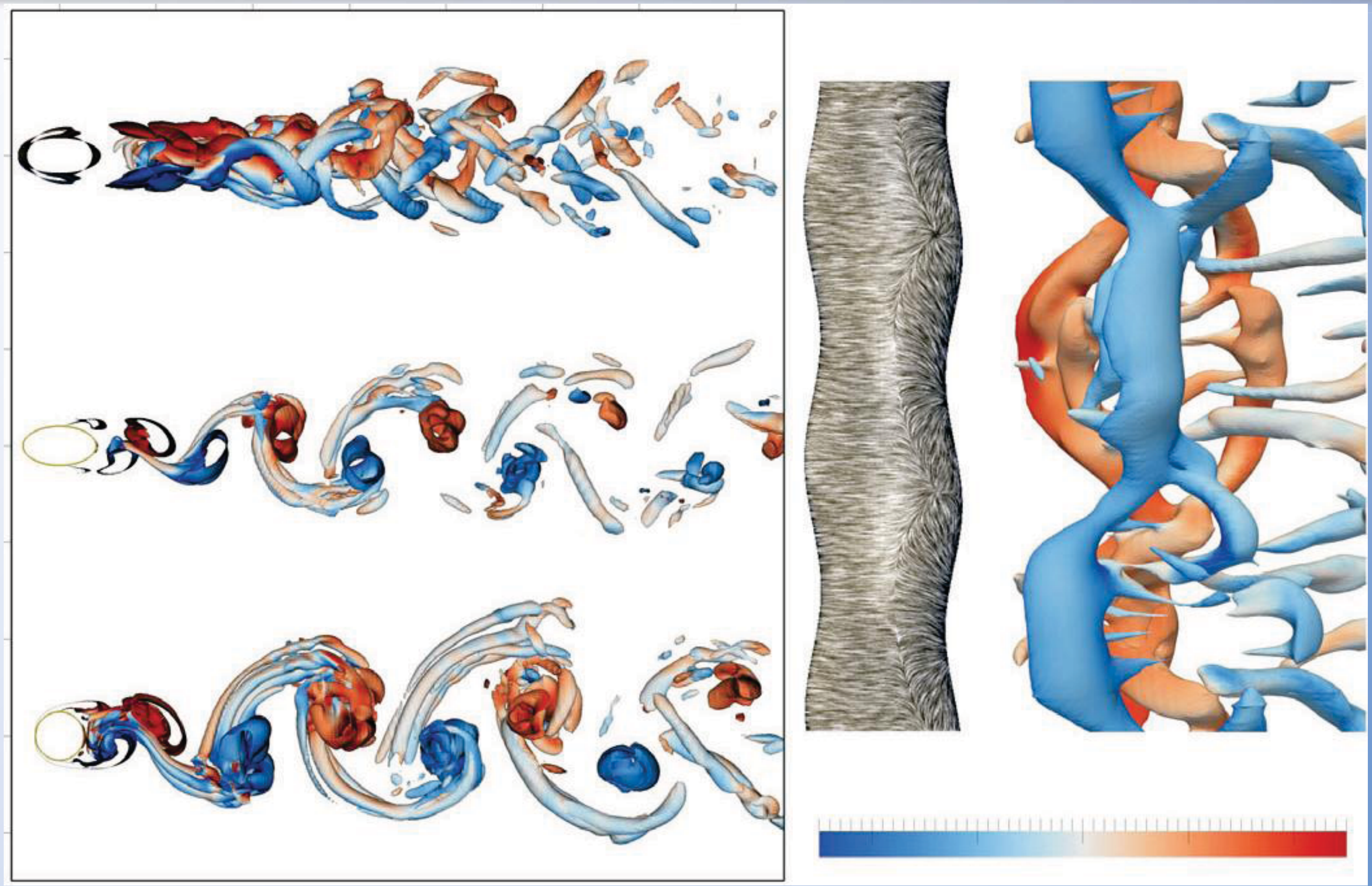
Seal whisker

Ellipse

Cylinder



Re = 500

PIV on vibrissae at U of Rostock. Witte et al. 2012. Figure shows Q-criterion

- 40% mean drag coefficient reduction over cylinder
- 90% reduction of unsteadiness

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Objectives – Fundamental Aero

- Use a holistic approach to
  - Achieve a fuel burn reduction of approximately 3%
  - Achieve noise Reduction of at least 2 db

  Through

  a. Passive Biomimicry
  b. Autonomous Closed-Loop Flow Control (ACFC)

- Biomimetics enables more aggressive design that will benefit further from ACFC
- While many applications have been studied, infinite possibilities remain

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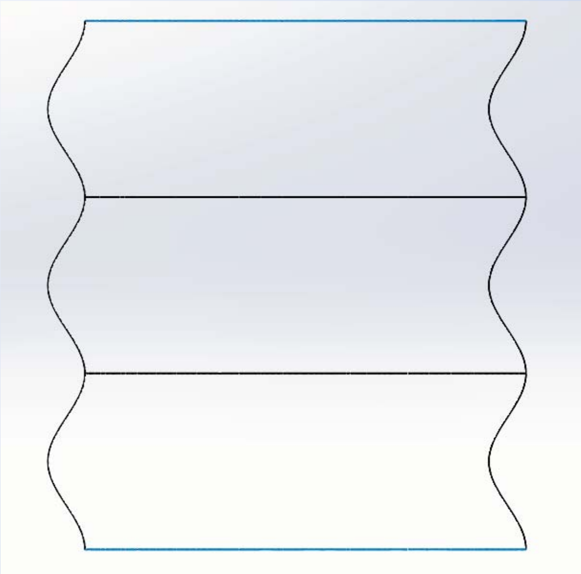
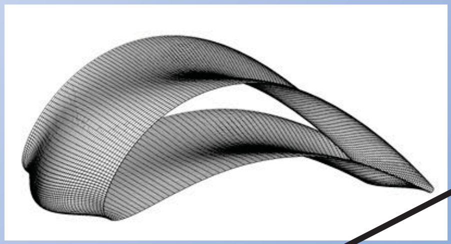
Biomimetic Features

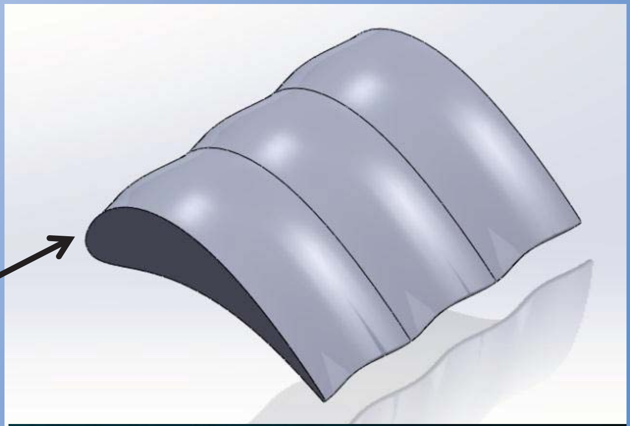
- Achieve delayed separation like seal whisker at High Re
- Achieve distributed wake like seal whisker
- Keep profile drag at or below baseline
- Keep pressure side flow largely unaffected to increase lift/power

Biomimetic Concept

- Create span-wise pressure gradient on suction side using span-wise undulations
- Push adverse gradient to valleys near trailing edge
- Trailing edge valleys occur at span-wise location of leading edge peaks
- Peaks transition to valleys at crown location







- Amplitude based on LE radius
- Pitch from Seal Whisker

Feasibility Study of Biomimetic Concept

- Potential flow solutions using MATLAB to understand span-wise pressure gradients
- Unsteady 3D CFD using Glenn-HT
  - Cp distribution at various span-wise locations
  - Average wake pressure-loss coefficient 10% chord downstream of TE
  - Multiple incidence angles
- Wind tunnel testing
  - SW2 cascade facility
  - Total pressure surveys at 10% chord downstream of TE
  - Hotwire surveys at 10% chord downstream of TE
  - Multiple incidence angles

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ACFC Concept

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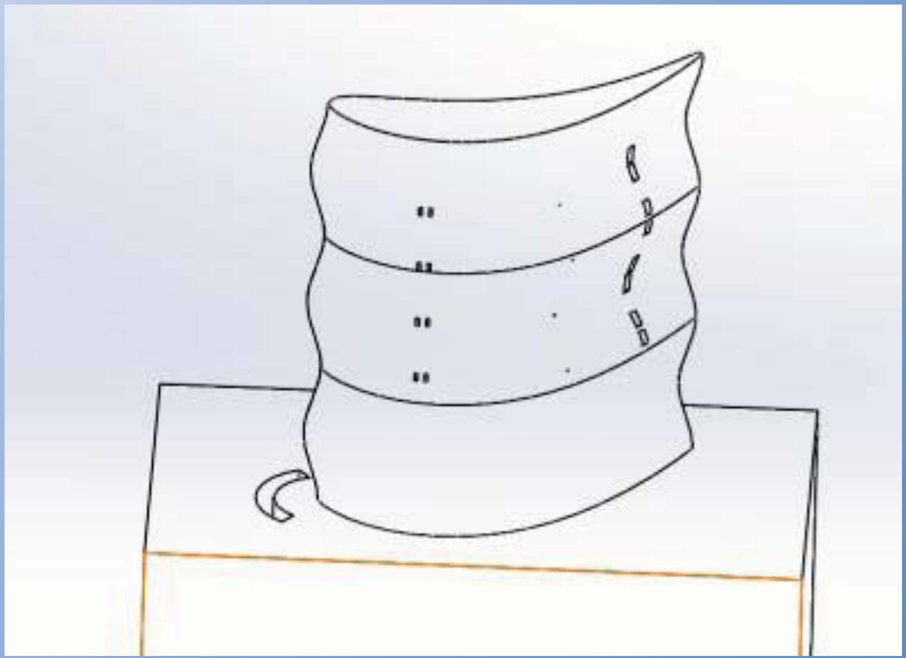
Use suction at the hub to divert BL from horseshoe vortex region and deliver it to regions of separation and TE. This needs to be accomplished without moving parts or external power.

Three Components:

1. Source for flow control
   - Slot upstream of LE on hub
   - Positioned for maximum suction
   - Positioned for maximum secondary flow reduction
2. Performance improvement
   - Pulsed flow at TE and SS
   - Spanwise distributed pulsing slots at TE based on owl feathers.
3. Fluidic control of flow
   - Diverters and pulsing fluidics
   - Manages flow from and to components



Feasibility Study of ACFC

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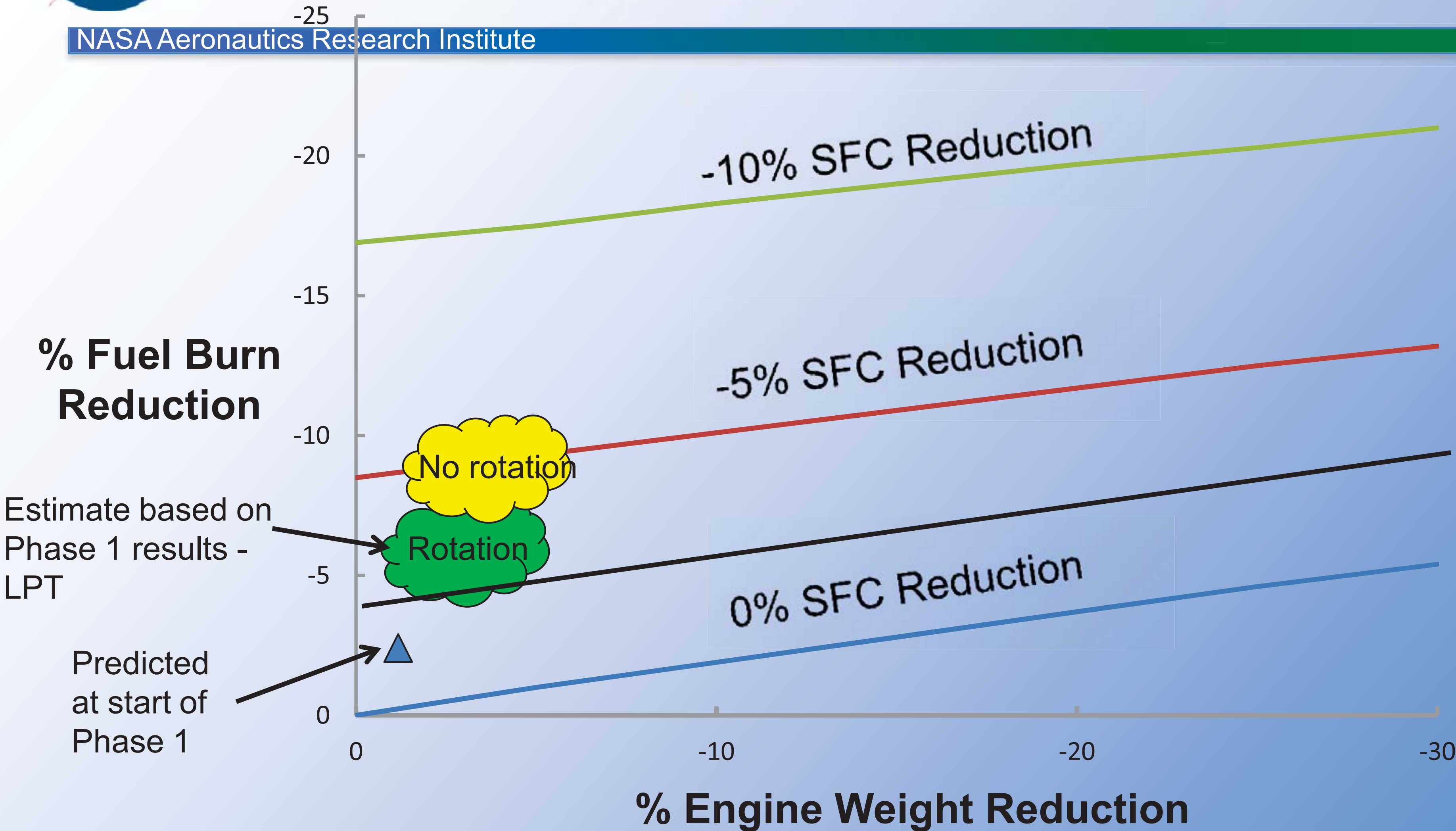
- 3D unsteady CFD
  - Suction slot upstream of horseshoe vortex saddle point
  - 3D simulation of fluidic actuators
- Wind Tunnel Tests
  - Trailing edge pulsing with hotwire survey
- Fluidic actuator testing using bench-top tests
  - Demonstrate repeatable consistent control
  - Demonstrate versatile control of single fluidic actuator using input signals
- Models created using FORTUS 250mc

Fuel Burn Sensitivities



» This was previous work for a 300 PAX aircraft
» Benefits might be slightly lower for N2A (767 class) aircraft

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Biomimicry

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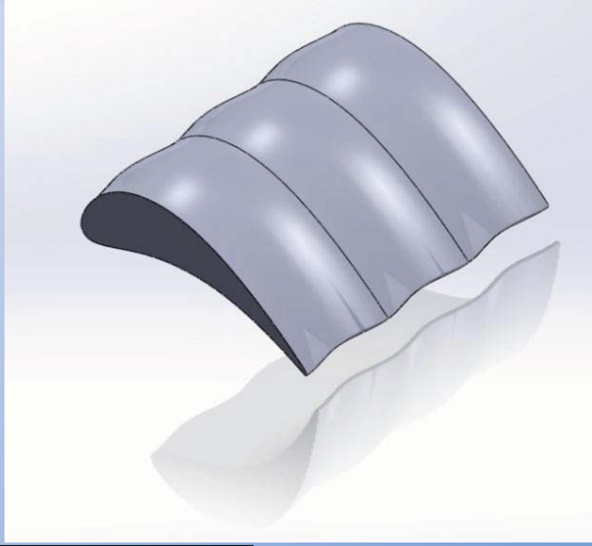
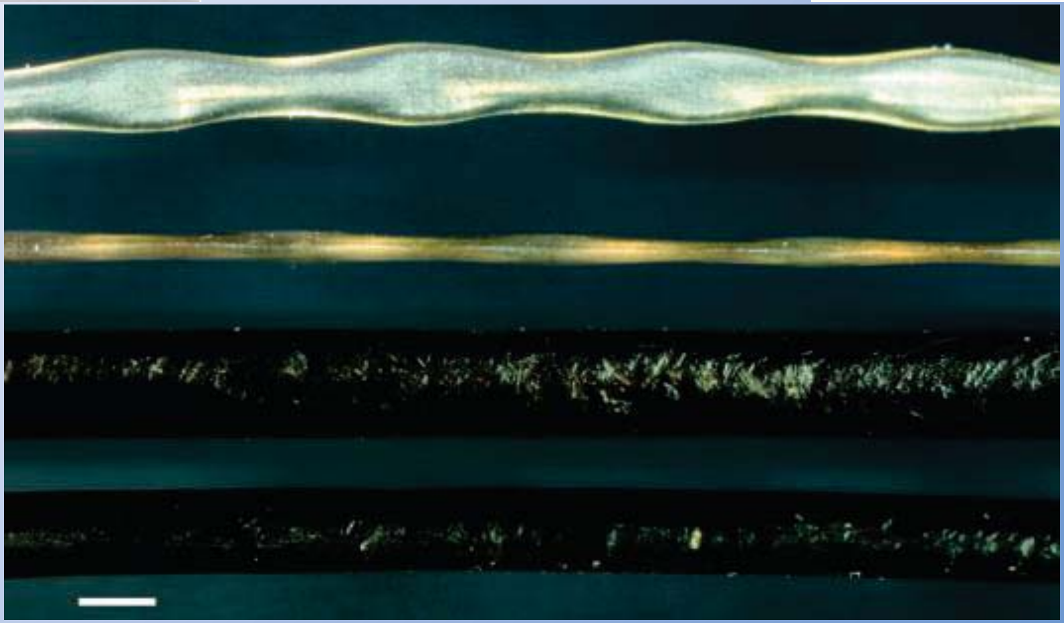


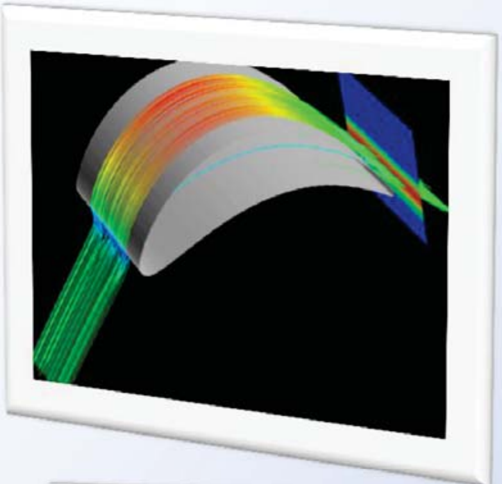


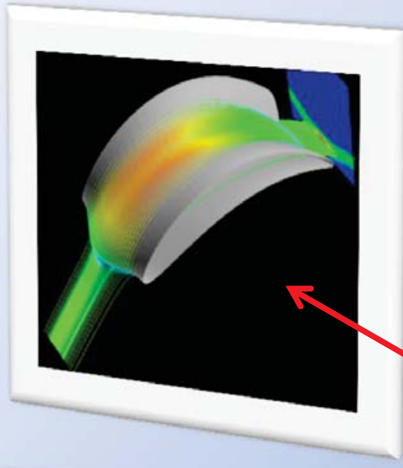
Hanke et al., “Harbor seal vibrissa morphology suppresses vortex-induced vibrations”, The Journal of Experimental Biology 213, 2665-2672 © 2010

Biomimicry – Seal Blade

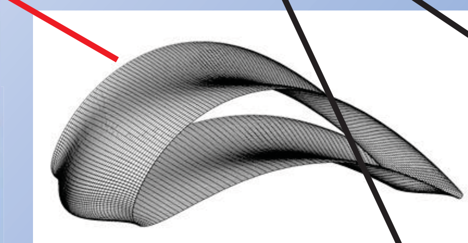
Rolls Royce VSPT

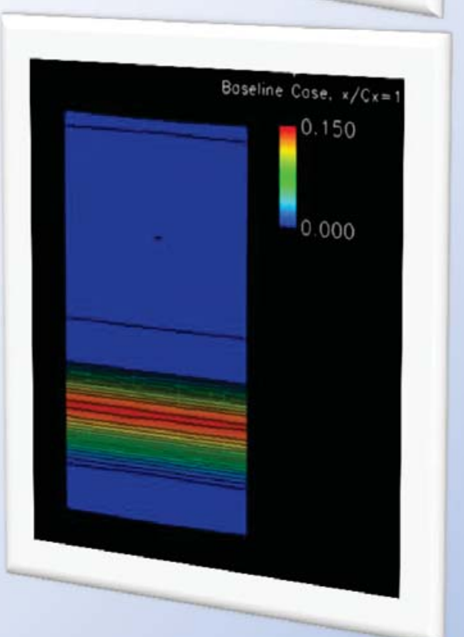
Seal Blade

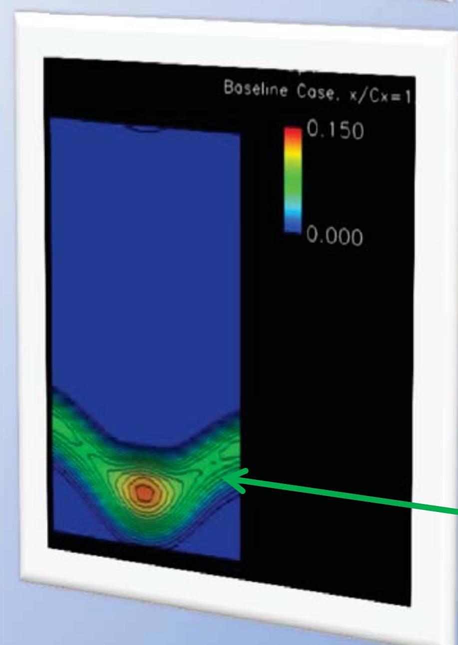




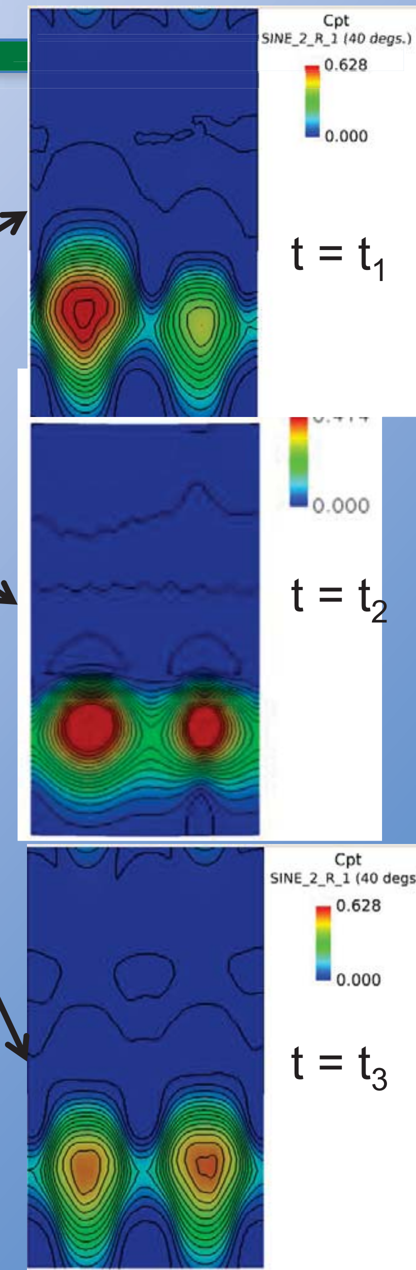
Noise reduction through wake control







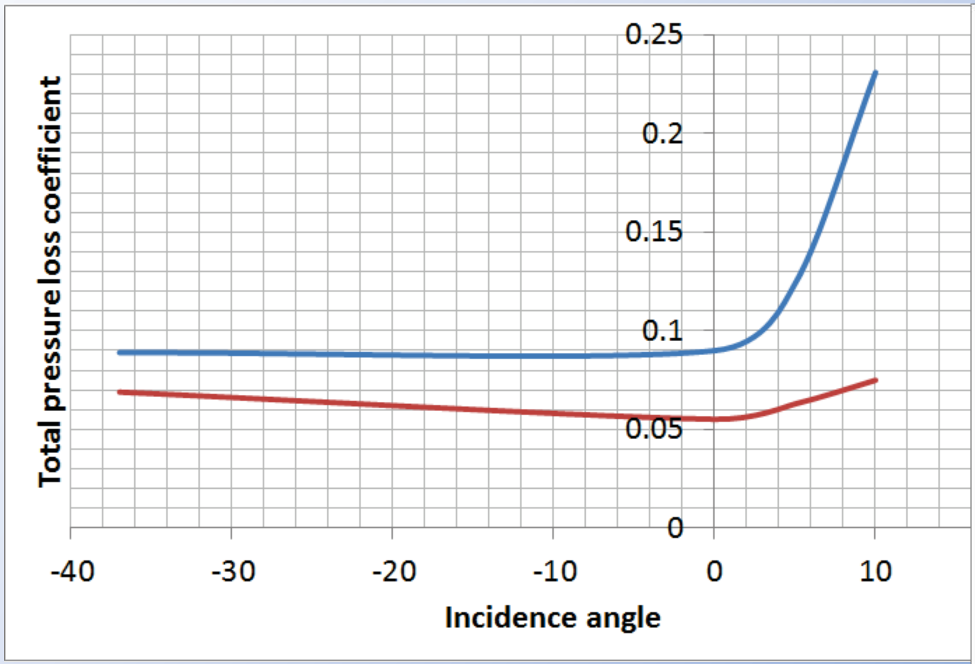
Fuel burn reduction due to elimination of separation

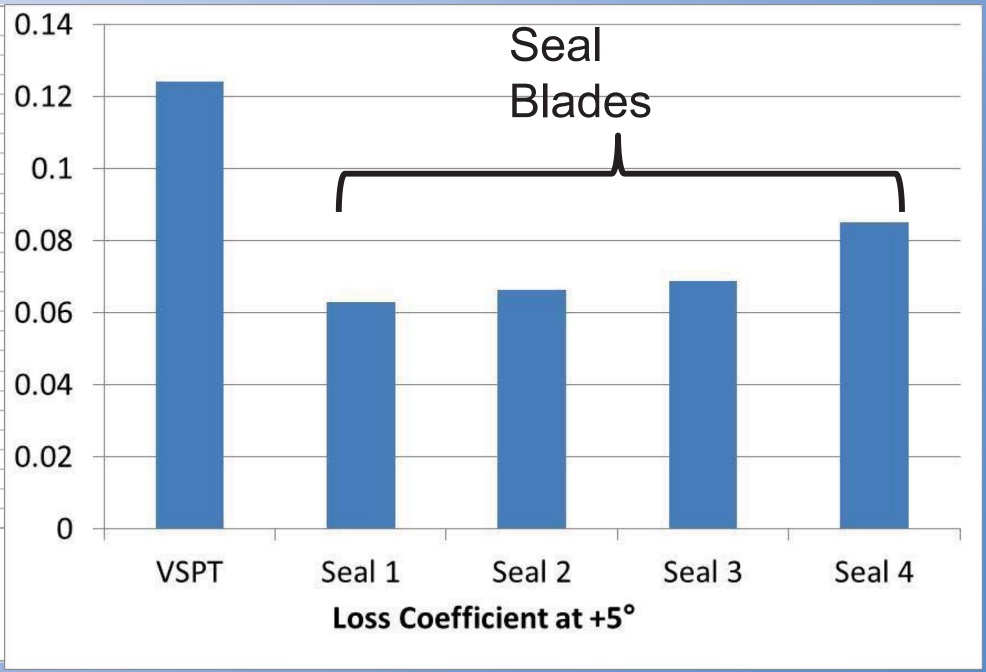


Biomimicry – Performance Improvements

Incidence tolerance over wide range leads to fuel burn reduction

50% improvement in pressure recovery leads to fuel burn reduction





Biomimicry – Seal Blade at 0° Incidence

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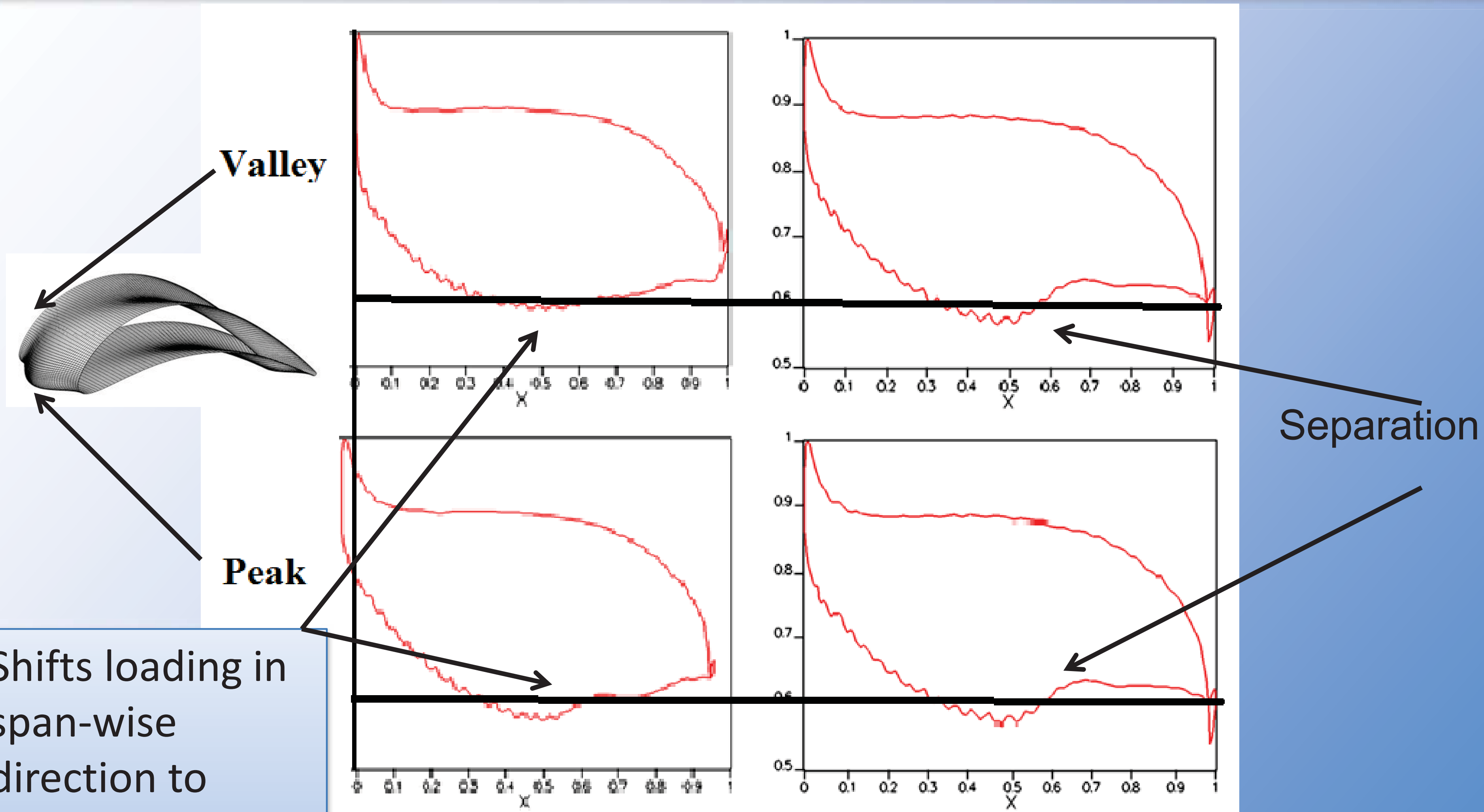
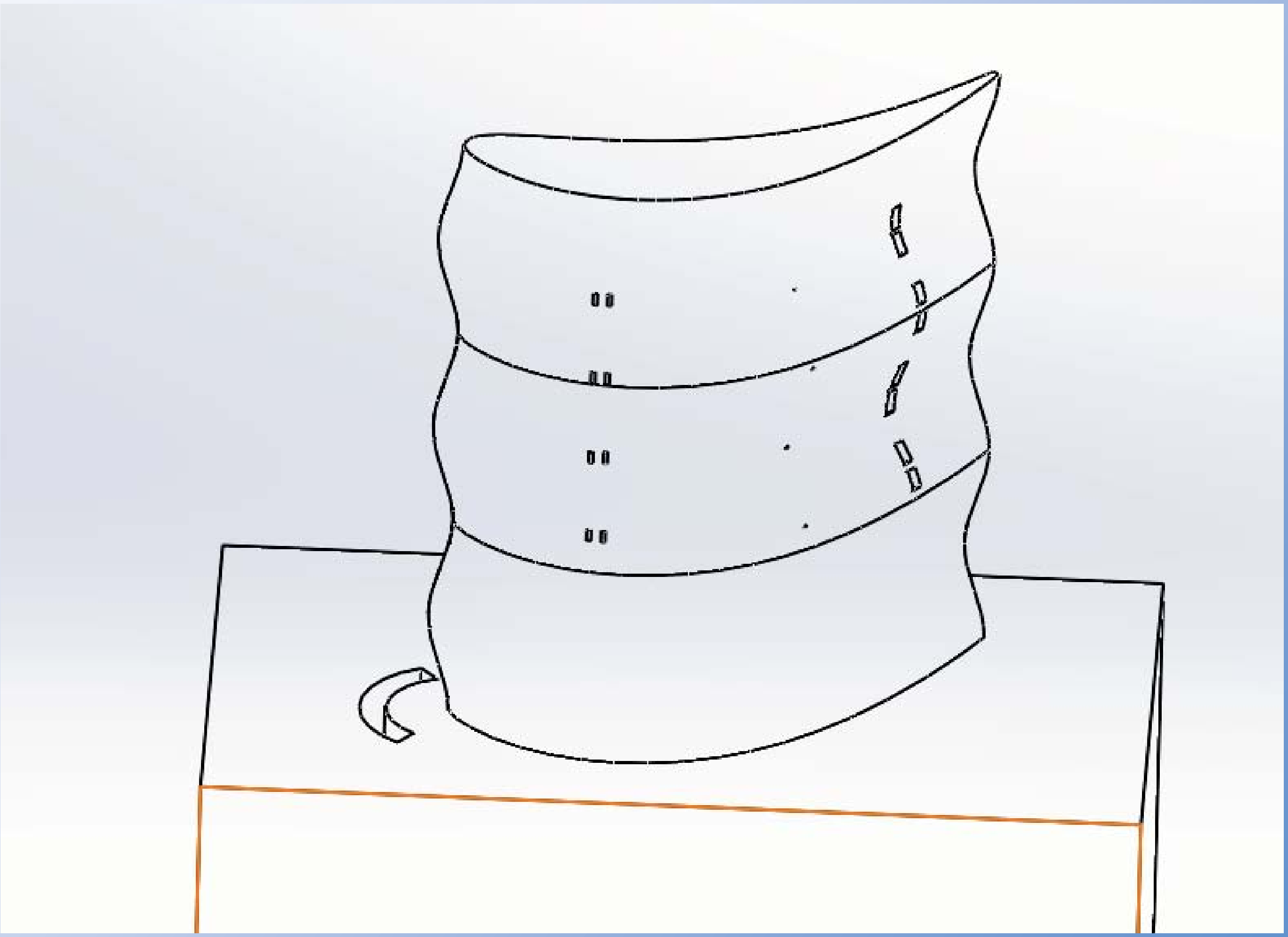


Seal Blade

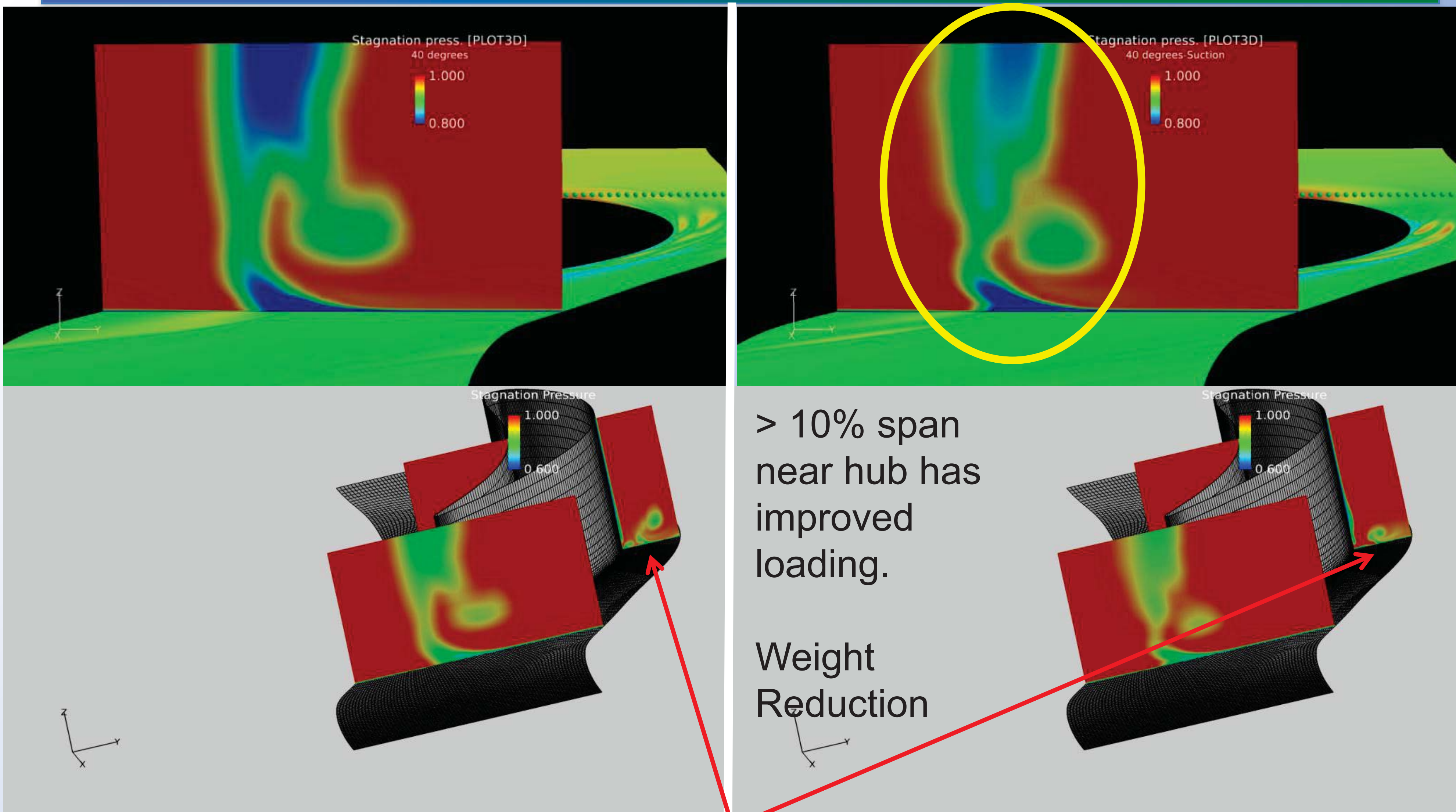
VSPT Blade - no modifications

- Shifts loading in span-wise direction to prevent separation.

Autonomous Closed-Loop Flow Control - ACFC



ACFC – BL Suction



> 10% span near hub has improved loading.

Weight Reduction

No suction

horseshoe

With suction

ACFC - Fluidic Devices

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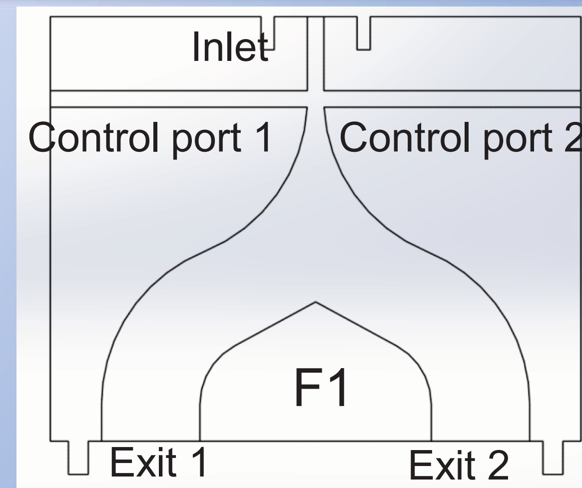
- Showed that for F1, repeatable consistent control is possible
- If port 2 is closed, port 1 controls jet exit such that flow always exits at 2 unless port 1 is closed
- If ports are both open, both control ports can be used to switch flow



Control port 1

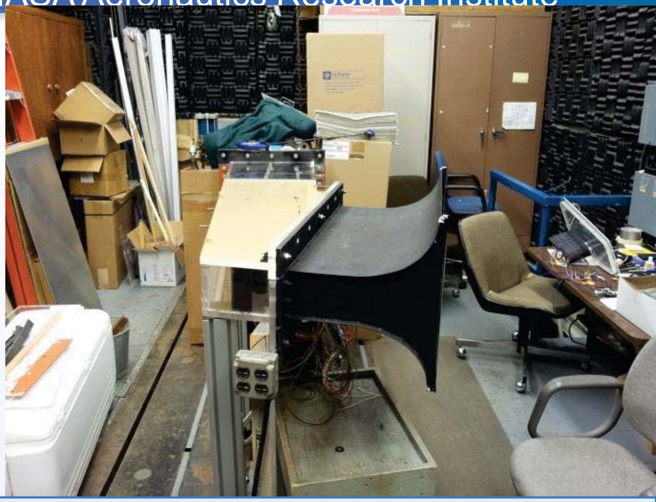
Control port 2

Exit 1

Exit 2

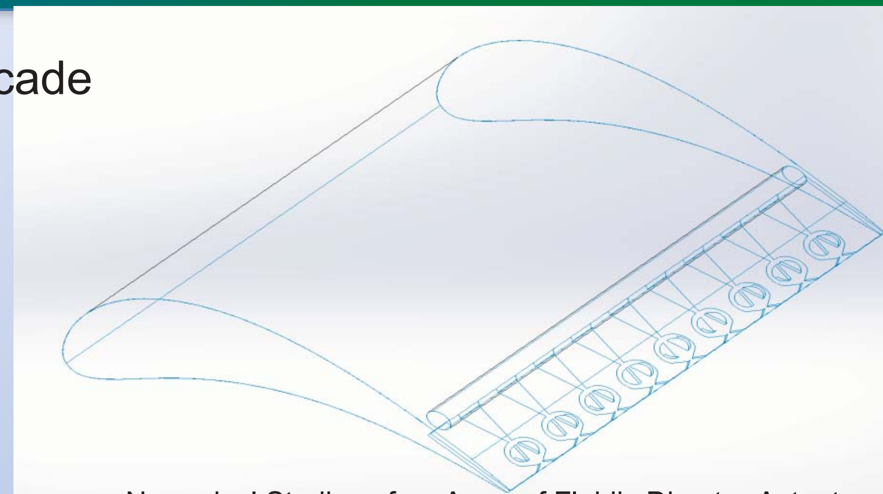
Exit indicator

ACFC – Trailing Edge Pulsing

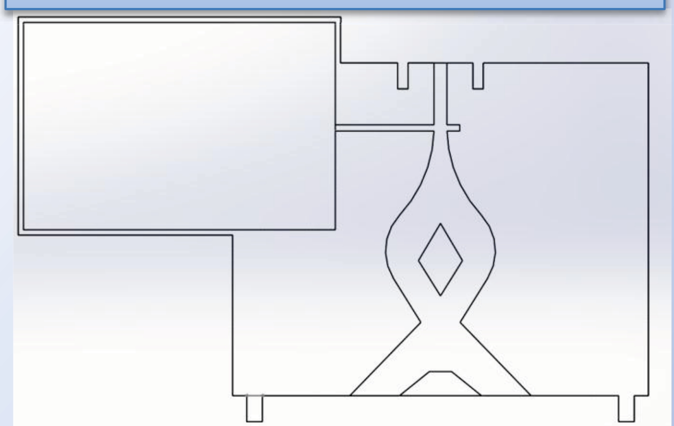


SW-2 cascade facility

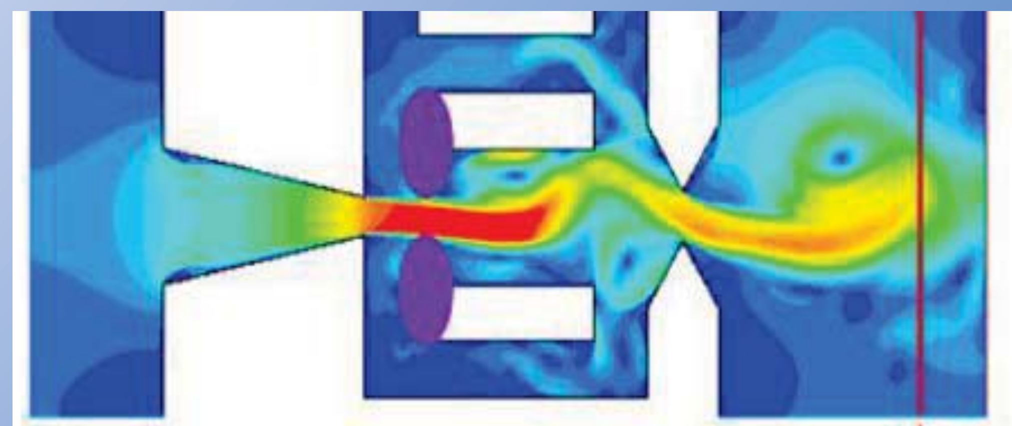
Testing in progress



Numerical Studies of an Array of Fluidic Diverter Actuators for Flow Control. Gokoglu, Suleyman ; Kuczmarski, Maria ; Culley, Dennis ; Raghu, Surya, 2011



Helmholtz sweeping fluidic device
New idea – testing in progress
Frequency independent of pressure ratio across device



Advanced Fluidics Inc. device with rapid switching. Inventor – Surya Raghu.
Frequency varies with pressure ratio and geometry

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ACFC – Concept Diagram

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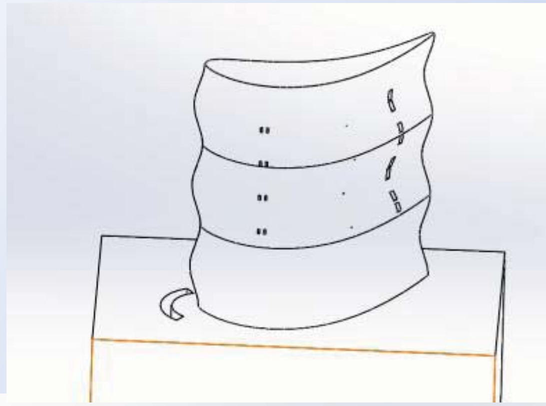
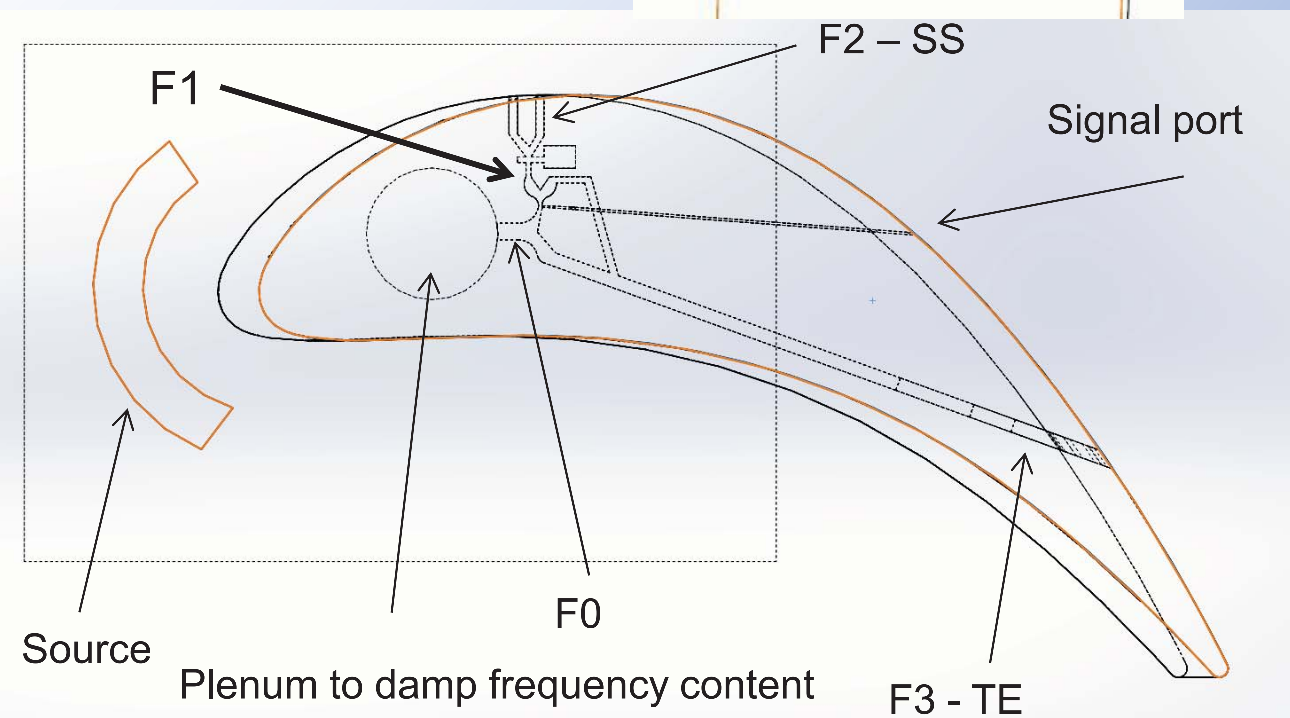
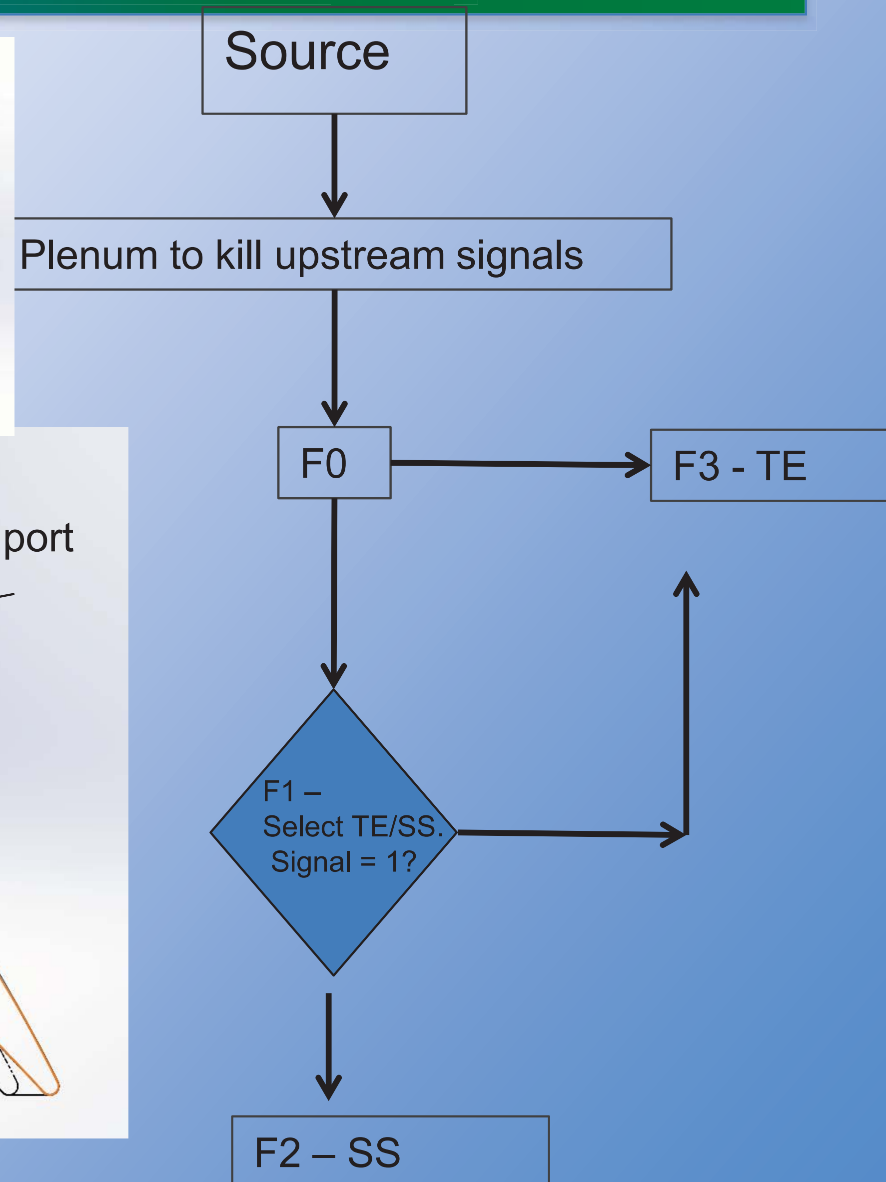
F0 – Brancher
F1 – Diverter
F2 – Pulser Helmholtz
F3 – Pulser Fluidic

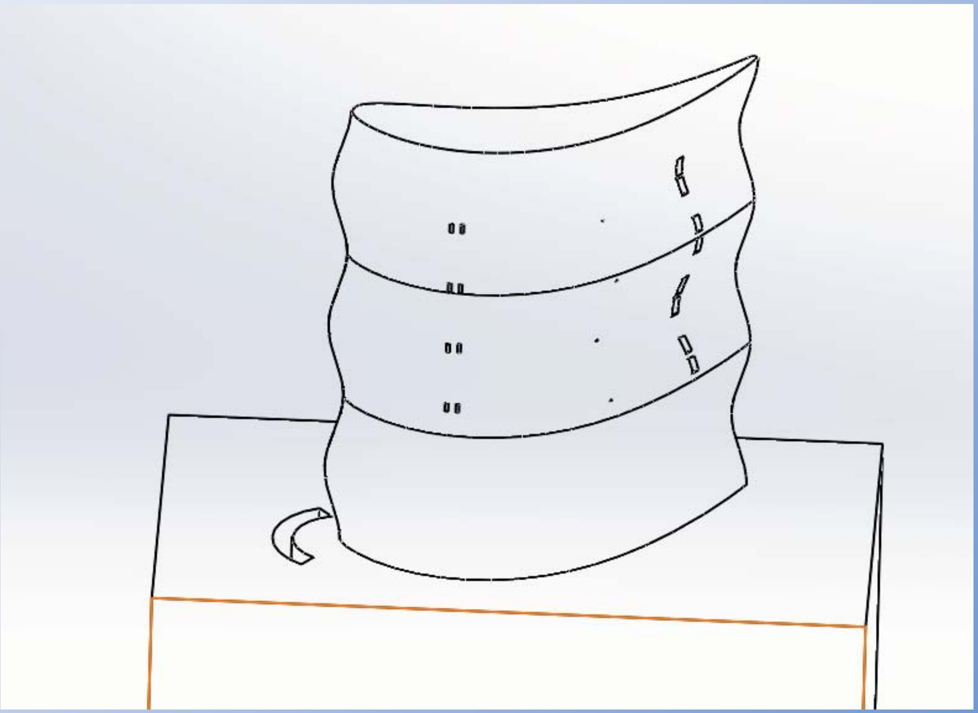






Combination of Biofoils and ACFC for Higher Loading

- A slot upstream of the Leading edge at the hub for suction
- Plenum to remove incoming signals
- Fluidic network to direct traffic and manage frequency content
- Biofoils to manage separation and incidence tolerance as well as regulate passage vortex and reduce noise
- Trailing edge slots with spanwise pulsing (adjacent slots pulse out of phase)



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Conclusions

- Feasibility of Biomimetic geometry shown for Fuel burn reduction
- Feasibility of Autonomous Closed-Loop Flow Control concept shown (waiting on TE pulsing results)
- Major benefit of this system is that no external power or electronics is required
- The system self-adjusts to changing flow conditions.
- At least 3% Fuel burn reduction and 2db noise reduction are possible
- More can be achieved by applying to fan, compressor, airframe

Patents Pending

- Holistic system concept
  - Endwall flow control
  - Wake noise reduction
  - Fluidic network concept
- Seal-type aerodynamic surface design
  - Electric cables, helicopter rotors, tail, turbine engine components
  - Parameters for optimization
- Helmholtz Fluidic switcher
- Porous owl-type aerodynamic surface
  - Mimicking of owl wing using virtual airfoil – LE and porous flow control
  - Low noise fan using synthetic owl feathers
  - Compliant wall for subsonic and supersonic flow control
- Novel flow visualization technique using water

Broader Applications

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- Fan blades – wakes, geometry
  - Owl type blades, porous blades
- Compressors – apply similar strategy for stall control
- Turbines
  - Porous trailing and LE. Possible to make a breathing airfoil to eliminate combustor tone?
- Combustor
  - Use fluidic to eliminate tone at source
- Sensors and probes
- Real-time flow measurement and visualization
- Landing gear, struts
- Electrical cables
- External flow – Landing Gear, Struts, Road Signs

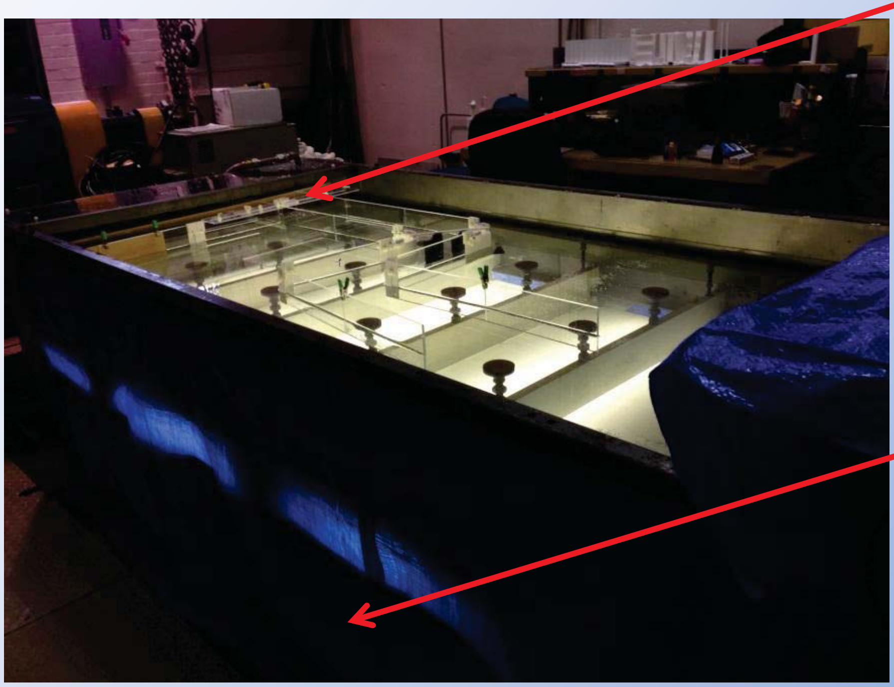
Path to Infusion

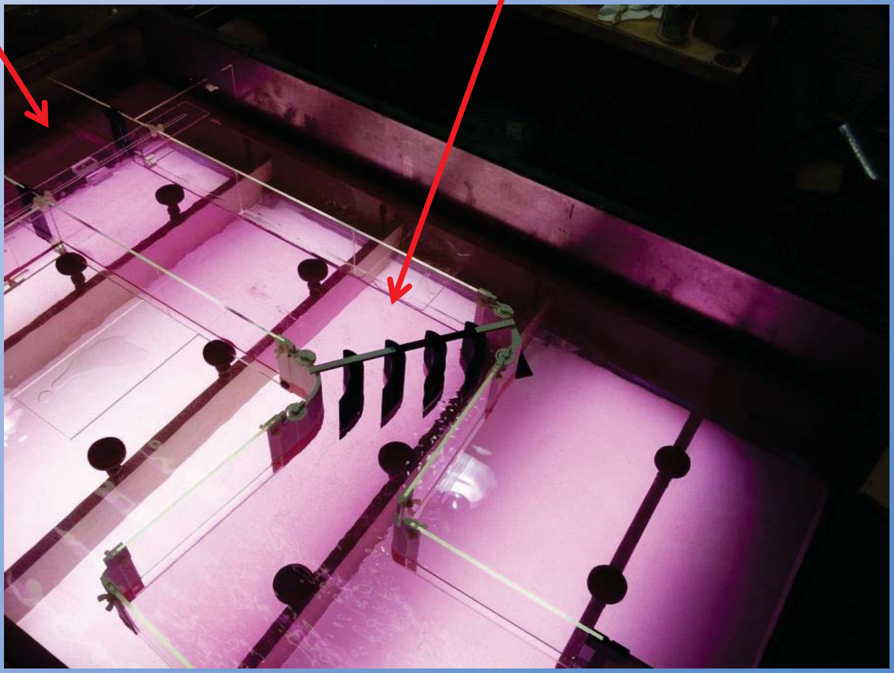
- Raise to TRL 3 in Phase 2
  - Include effect of rotation
  - Apply biomimetics to fan and compressor blades
  - Pulsed blowing for fan noise reduction
  - Fabricate and test complete fluidic network on benchtop
  - Test fluidic network within RR VSPT blade in SW-2
  - CW-22 testing at matched Re and Mach
  - Optimization of geometry using COMSOL/MATLAB/Solidworks
  - Extend Seedless Velocimetry measurement methods
  - Testing of biomaterials in SW-2, water table

- Elements are of interest to
  - Fixed Wing – propulsion efficiency, acoustics
  - Aerosciences – Flow Control, Novel measurement techniques

Flow Visualization for Phase 2

- Water table set up in SE-1 facility
- Instrumentation installed – XBOX Kinect, IR camera, scales for depth measurement
- Further upgrades in progress





Dye Injection - Visible

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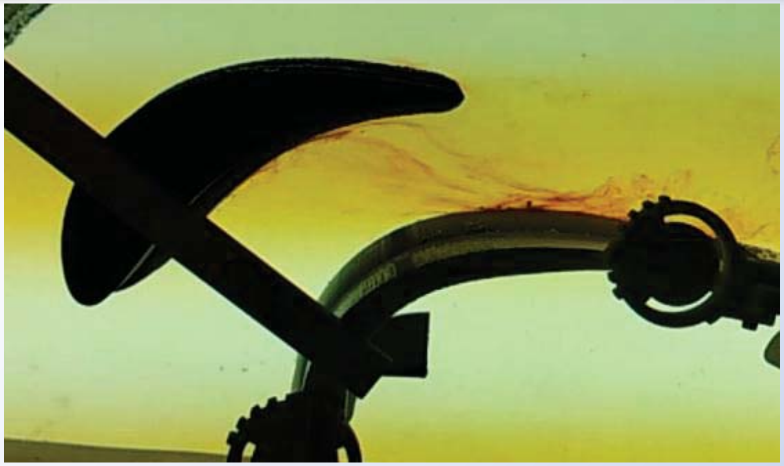
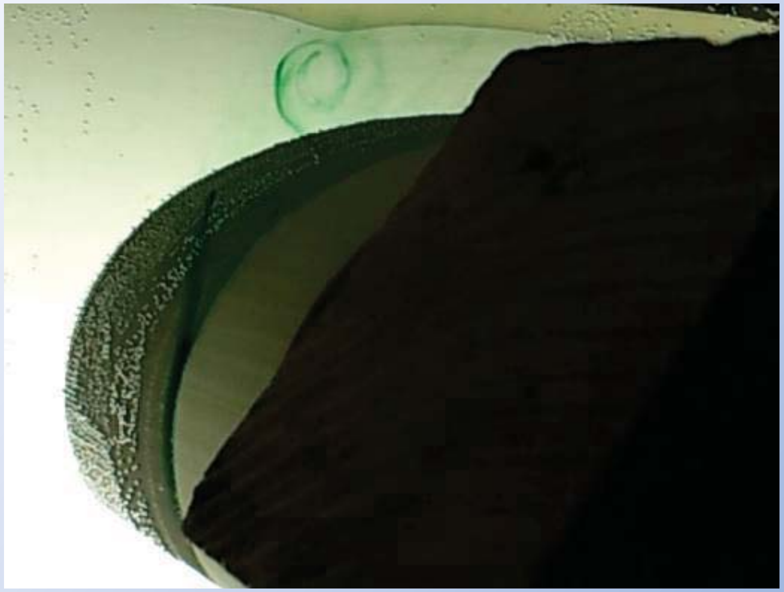
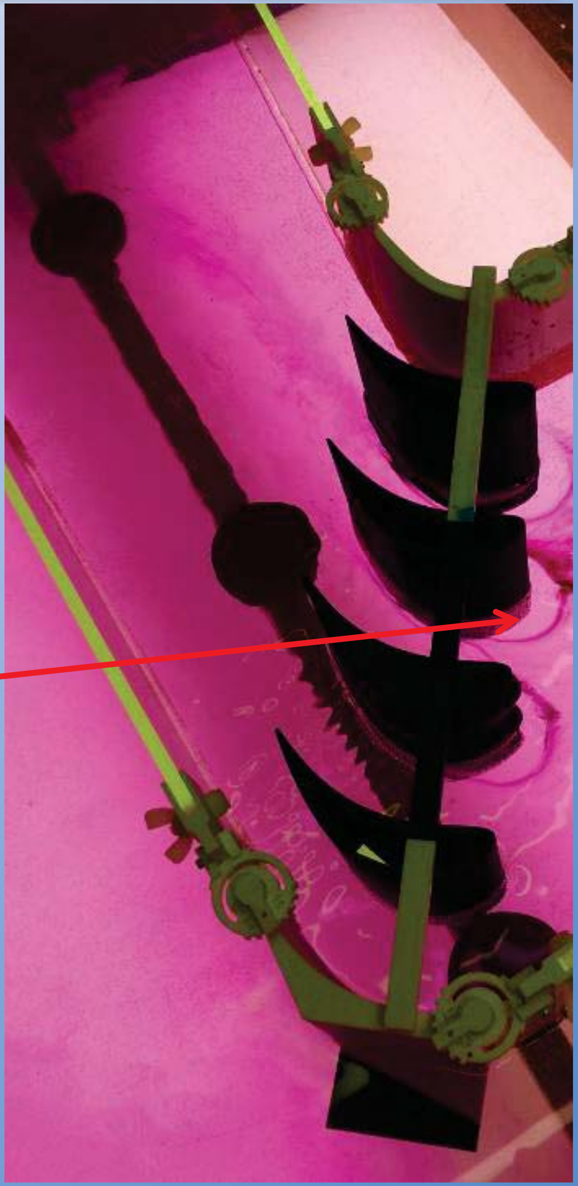


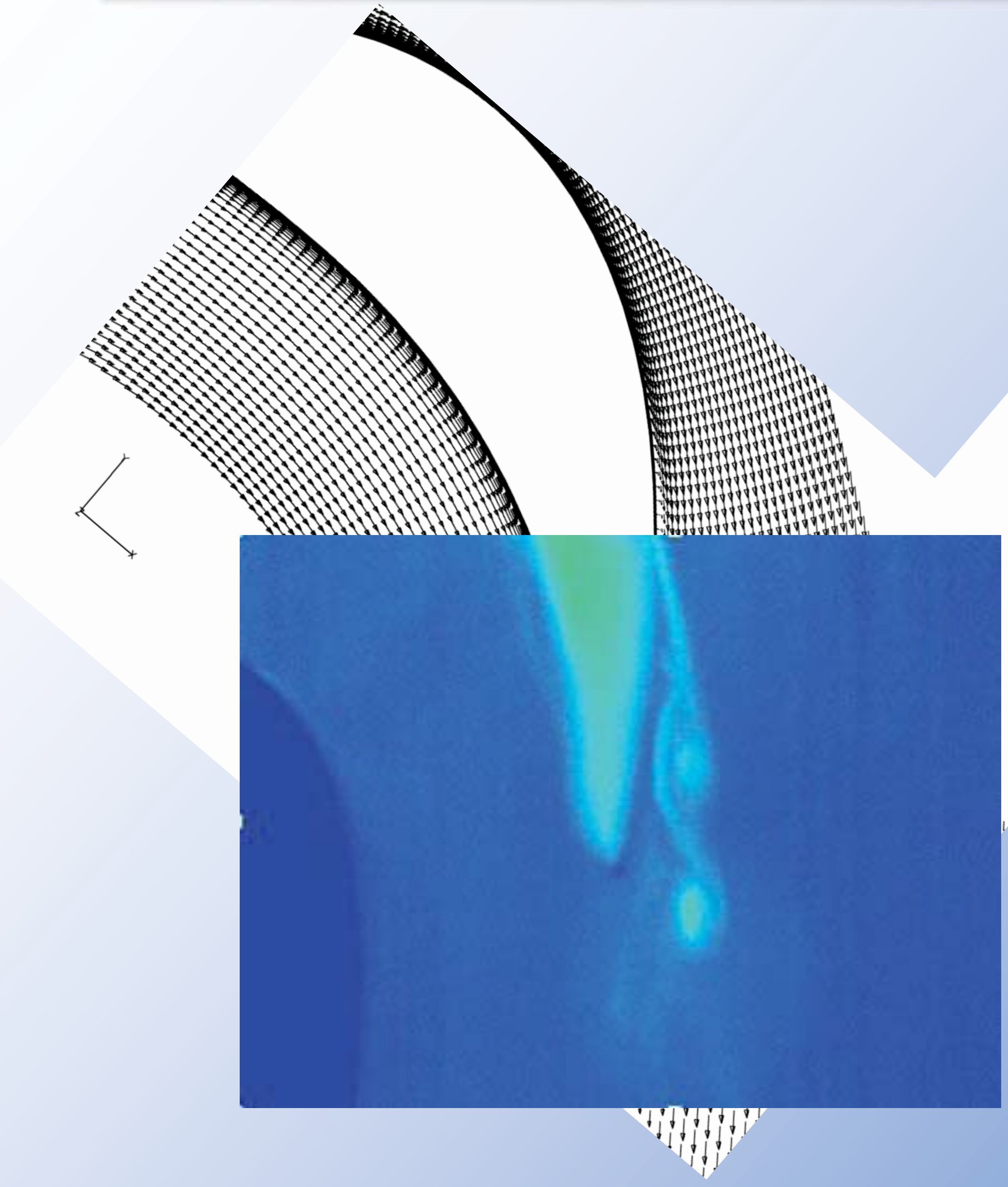
IR camera view

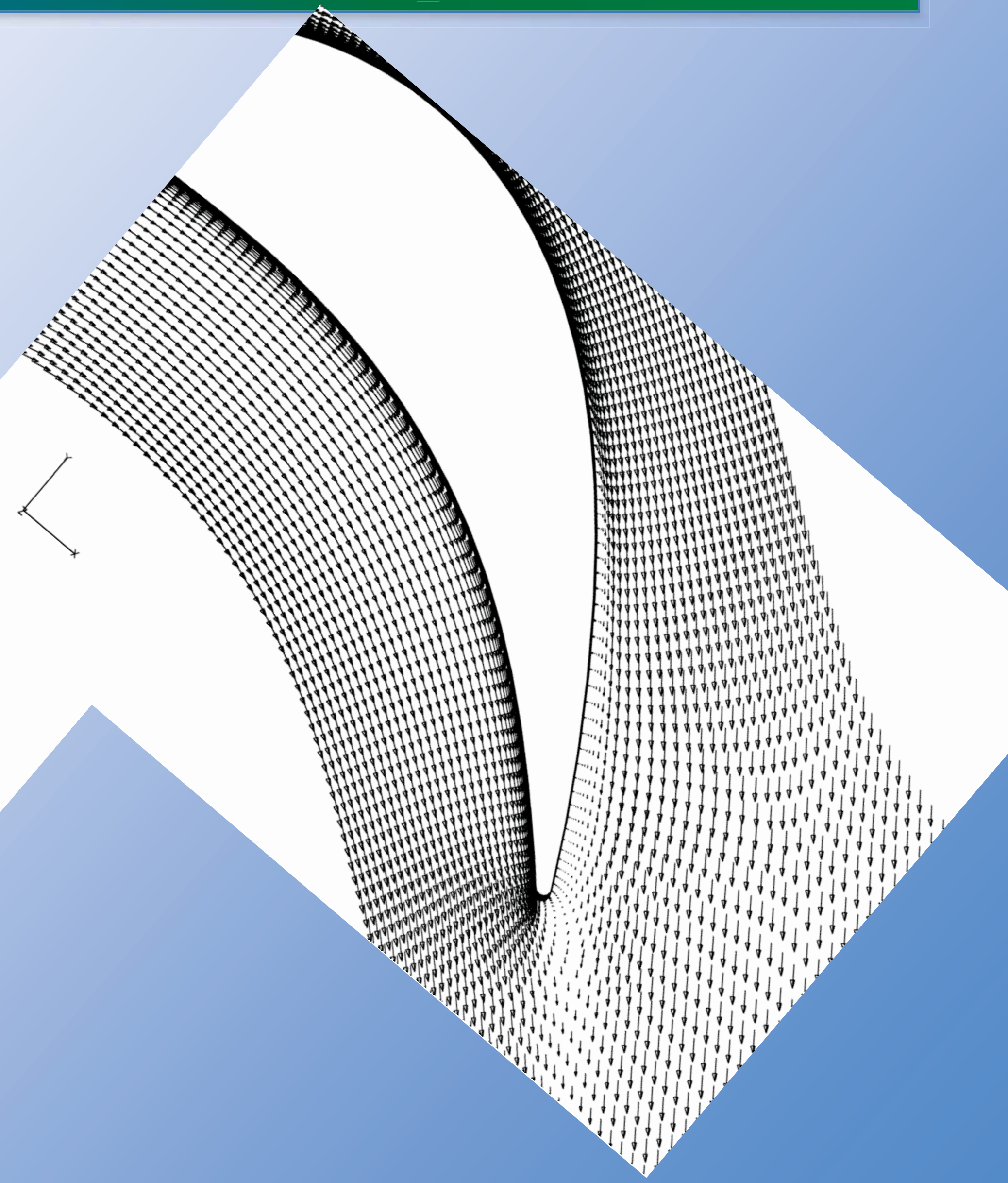


Horseshoe location



Infrared Flow Vis.





Real-time Quantitative Flow Vis.

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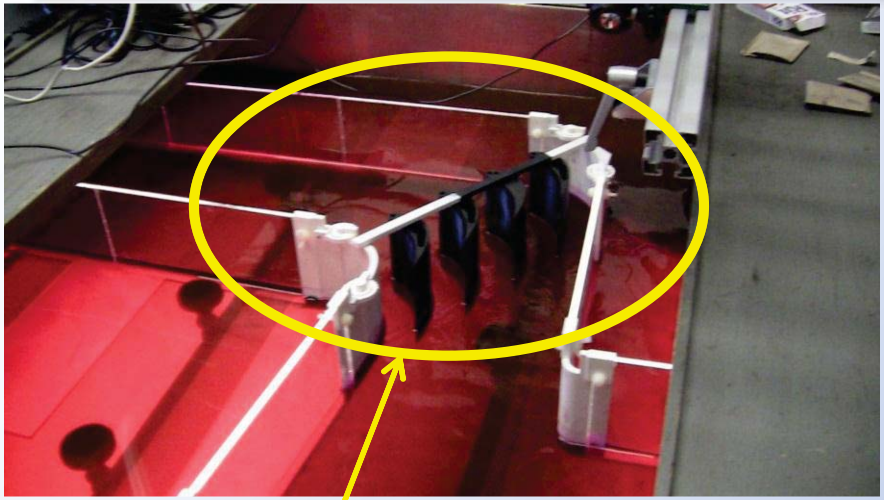
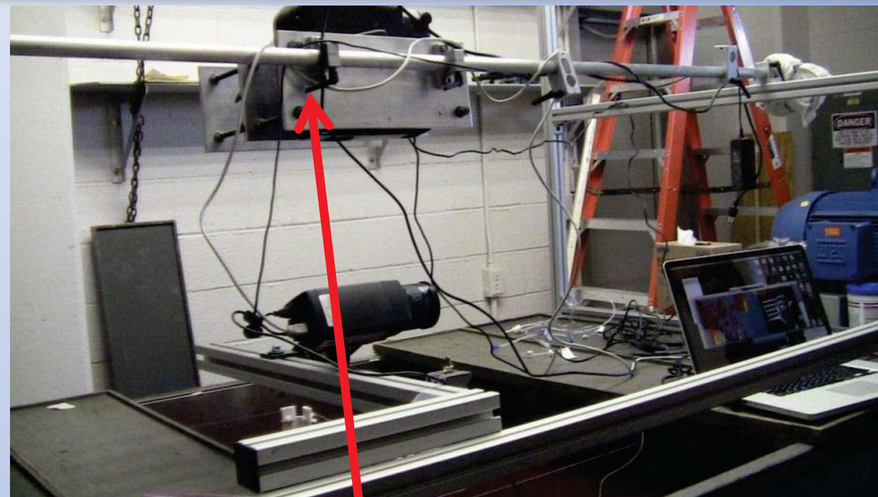
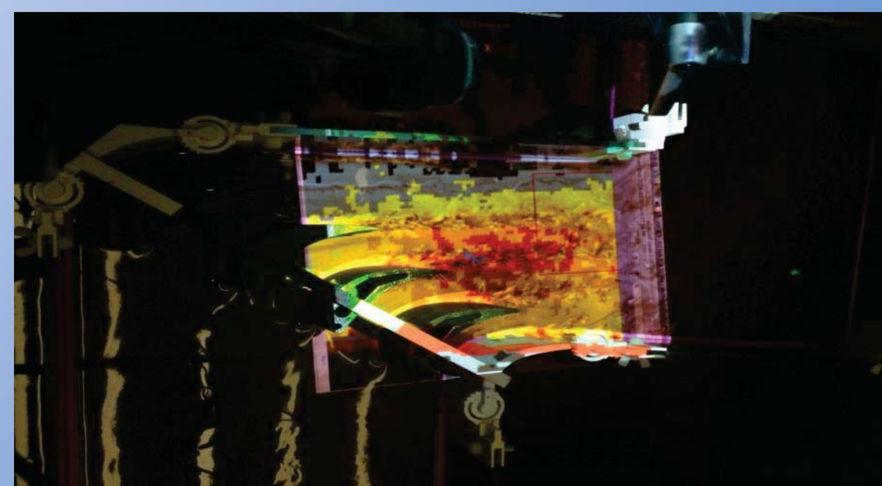




Cascade

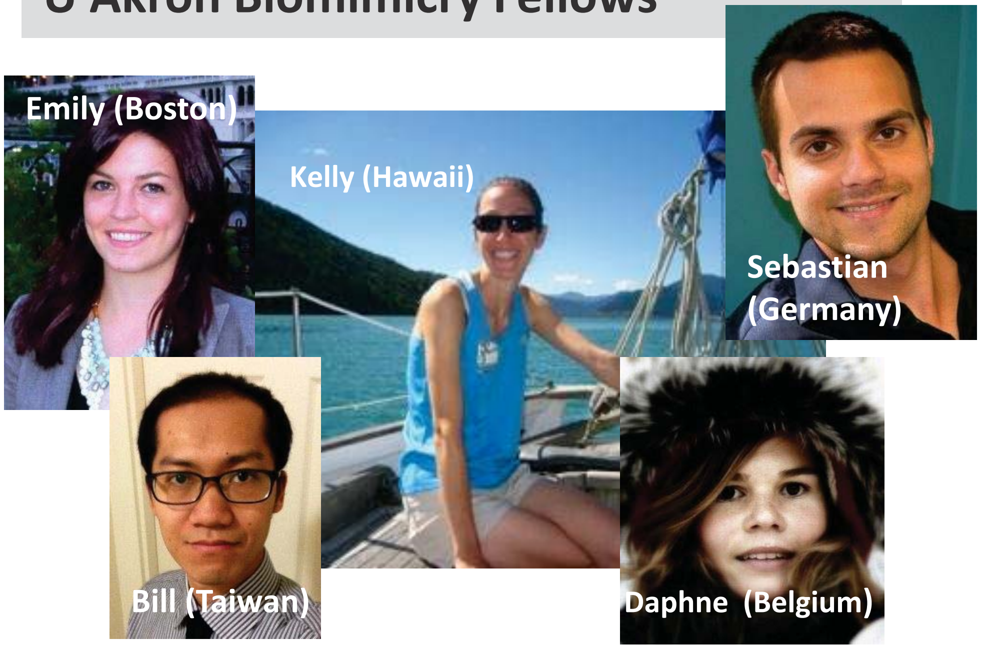
XBOX Kinect and projection system



Phase 2 Collaboration - External

- Microsoft
- Harp technology
- Advanced Fluidics
- Georgia Tech
- Cleveland State University
- Marine Mammal Center, San Diego
- Cleveland Zoo
- GLBio

U Akron Biomimicry Fellows



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BIOMIMICRY 3.8

Biomimicry Operationalizes Sustainability

Acknowledgements

- Trong Bui, Albion Bowers, Jennifer Cole (NASA DFRC)
- Ali Ahmadi (Cal Poly, Pomona)
- Jim Heidmann, Gwynn Severt, Jerry Welch, Michael Hathaway, Dennis Huff, D.R. Reddy, Mark Celestina, Milind Bakhle (NASA GRC), GVIZ team, Ed Envia, Brian Fite, Dan Sutliff, Danielle Koch, Chris Miller, Colin Creager (SLOPE team)
- Krish Ahuja (Georgia Tech)

Seal Blade Flow Visualization

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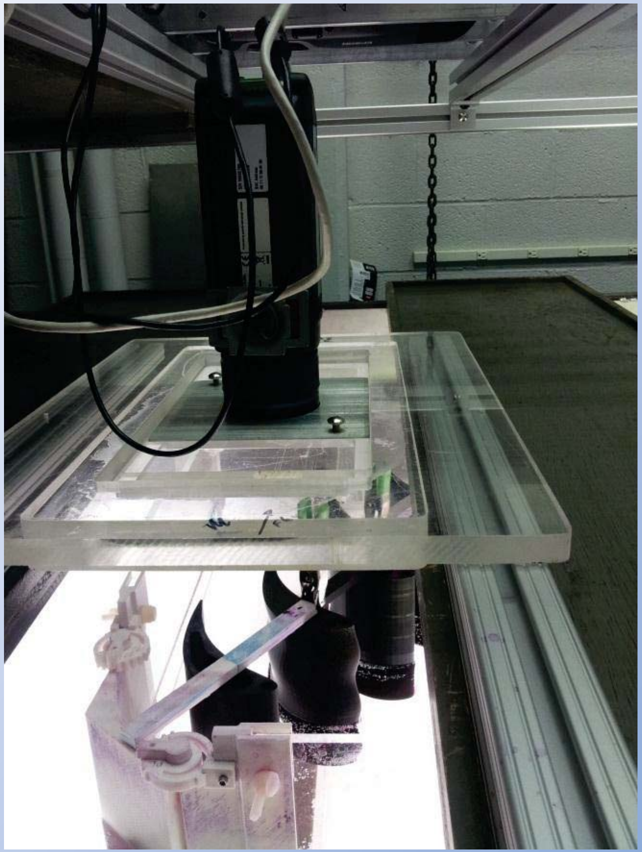
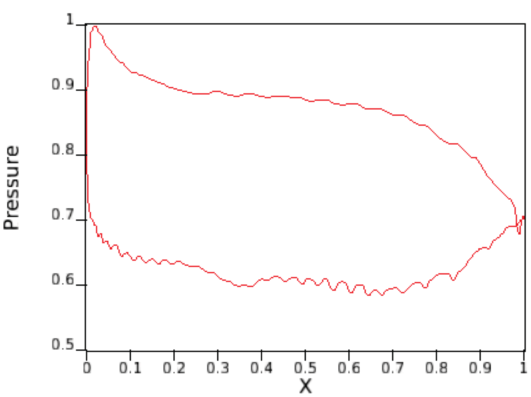
VSPT – 0 incidence

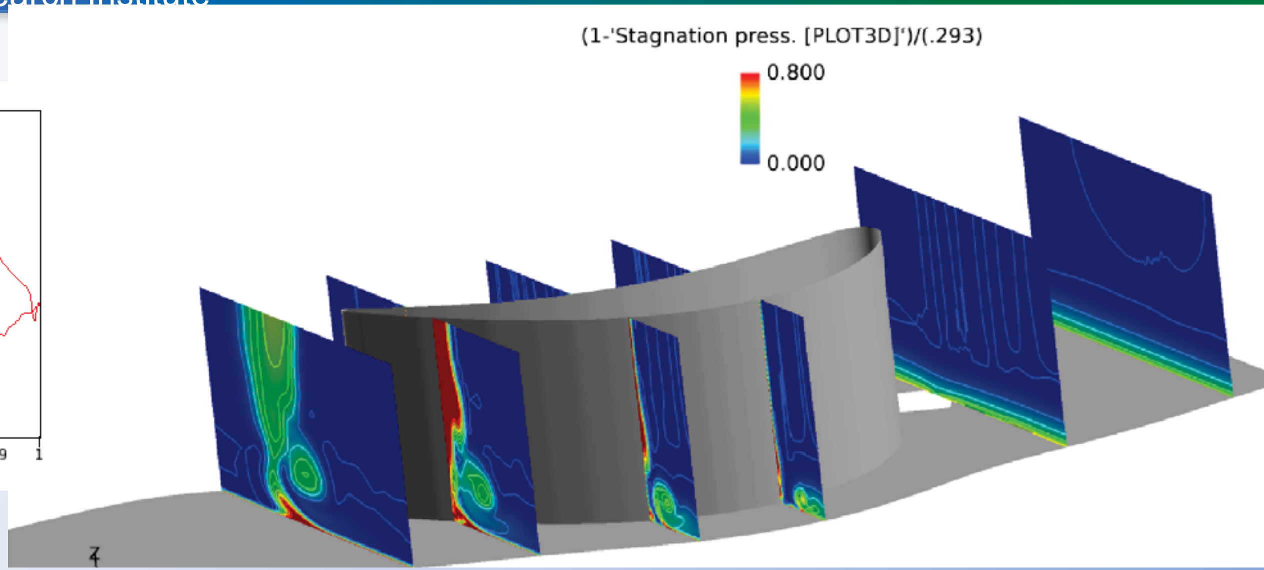


IR Setup

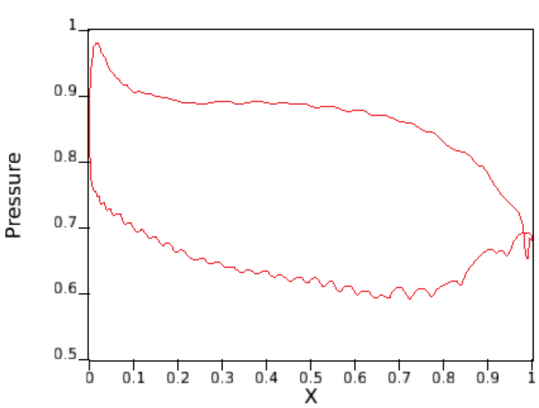
Seal Blade – 0 incidence

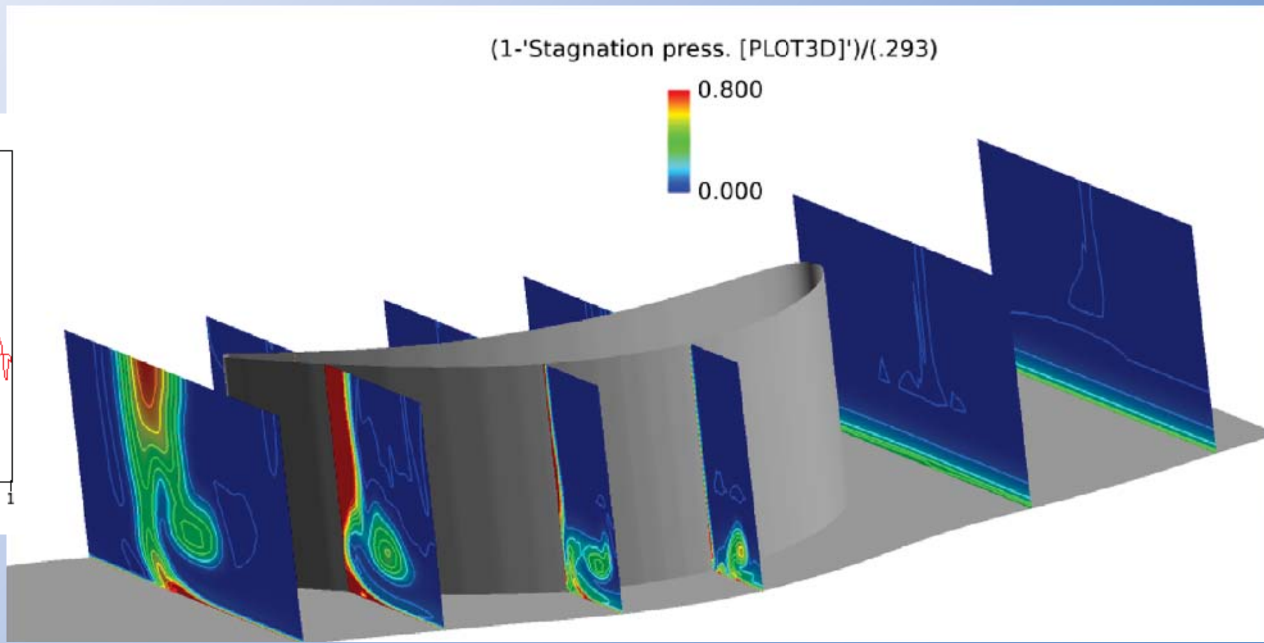
ACFC Suction Results





With Suction





Without Suction

ACFC Prototype Demo

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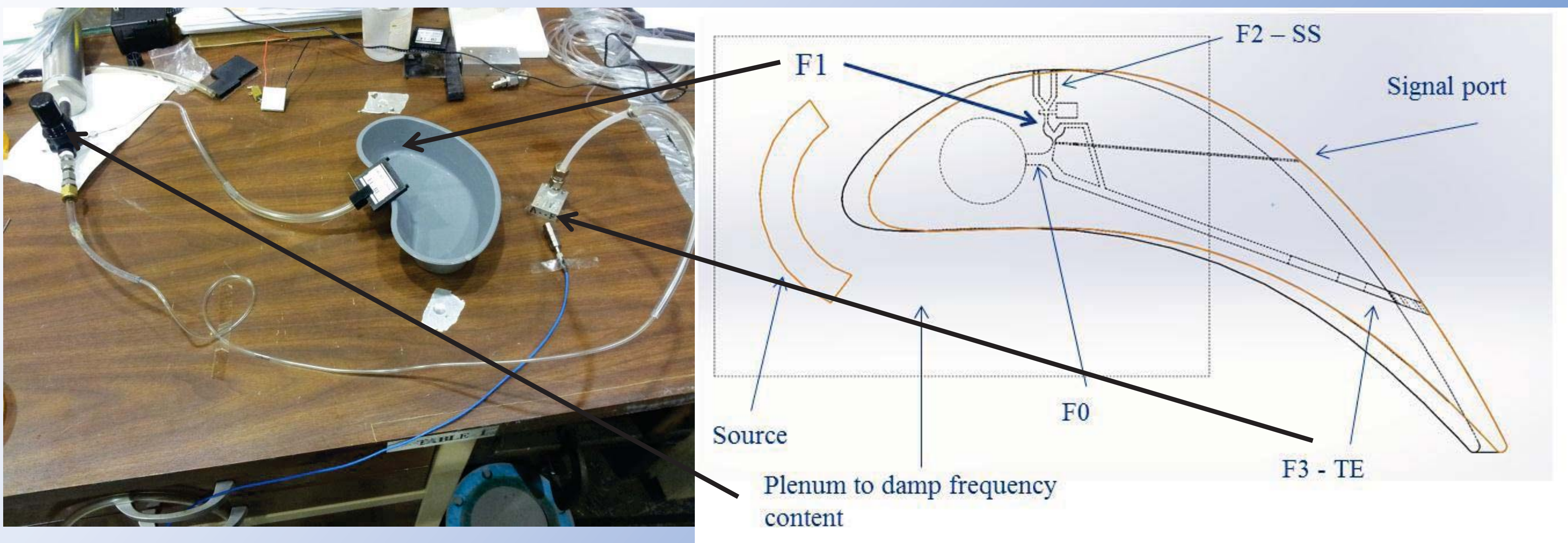

Fluidic Tests

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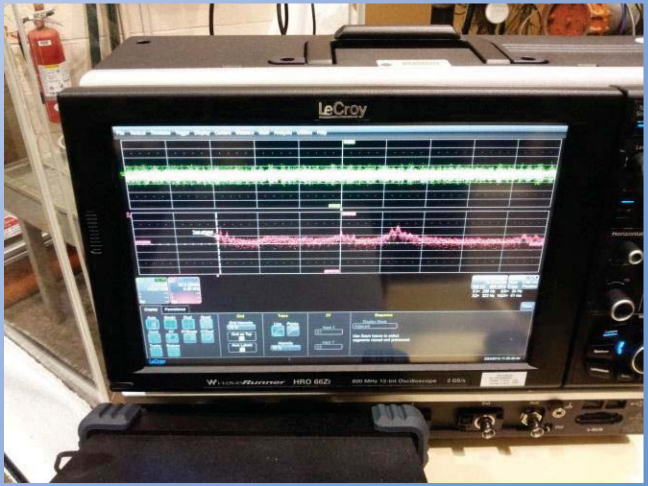


Engine/Aircraft Sizing Primer

- Engines can impact an aircraft's fuel burn through 2 means
  - » Improved Efficiency (i.e., reduced SFC)
  - » Reduced Engine (Pod) Weight

- Efficiency improvements typically have greater impact on large, long range aircraft
  - » 1% SFC improvement = ~1.67% block fuel reduction (300 PAX)
  - » 1% SFC improvement = ~1.33% block fuel reduction (RJ)
  - » 1% SFC improvement = ~1.20% block fuel reduction (LCTR2)

  (25% larger impact on Large Twin vs. Regional Jet, 40% larger vs.LCTR2)

- Engine weight reduction can also provide important fuel burn savings as aircraft size increases
  - » 5% engine wt reduction = ~1% block fuel reduction (300 PAX)
  - » 5% engine wt reduction = ~0.6% block fuel reduction (RJ)
  - » 5% engine wt reduction = ~0.5% block fuel reduction (LCTR2)

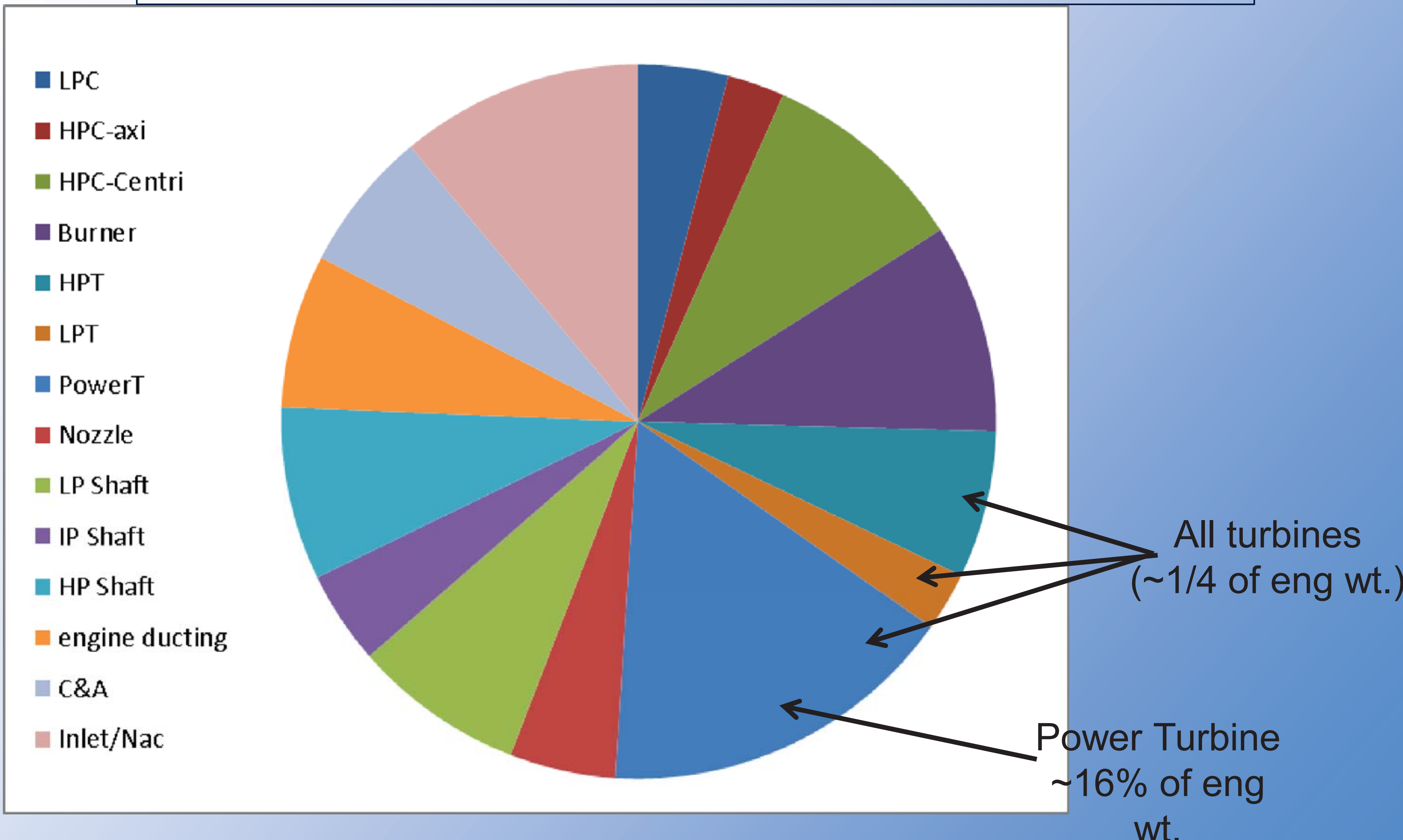
  (67% larger impact on Large Twin vs. Regional Jet, twice [2x] vs. LCTR2)

- Turbofan engines on larger aircraft typically have higher bypass ratios which reduces weight fraction of turbine blade/vanes, effect even more pronounced for turboshaft engines

Weight Breakdown on LCTR2 Advanced Engine

"standard" 2-stage power turbine (PT)

In turboshaft engines, Turbines are major weight components



Weight Breakdown on LCTR2 Advanced Engine

4-stage Variable-Speed Power Turbine (VSPT)

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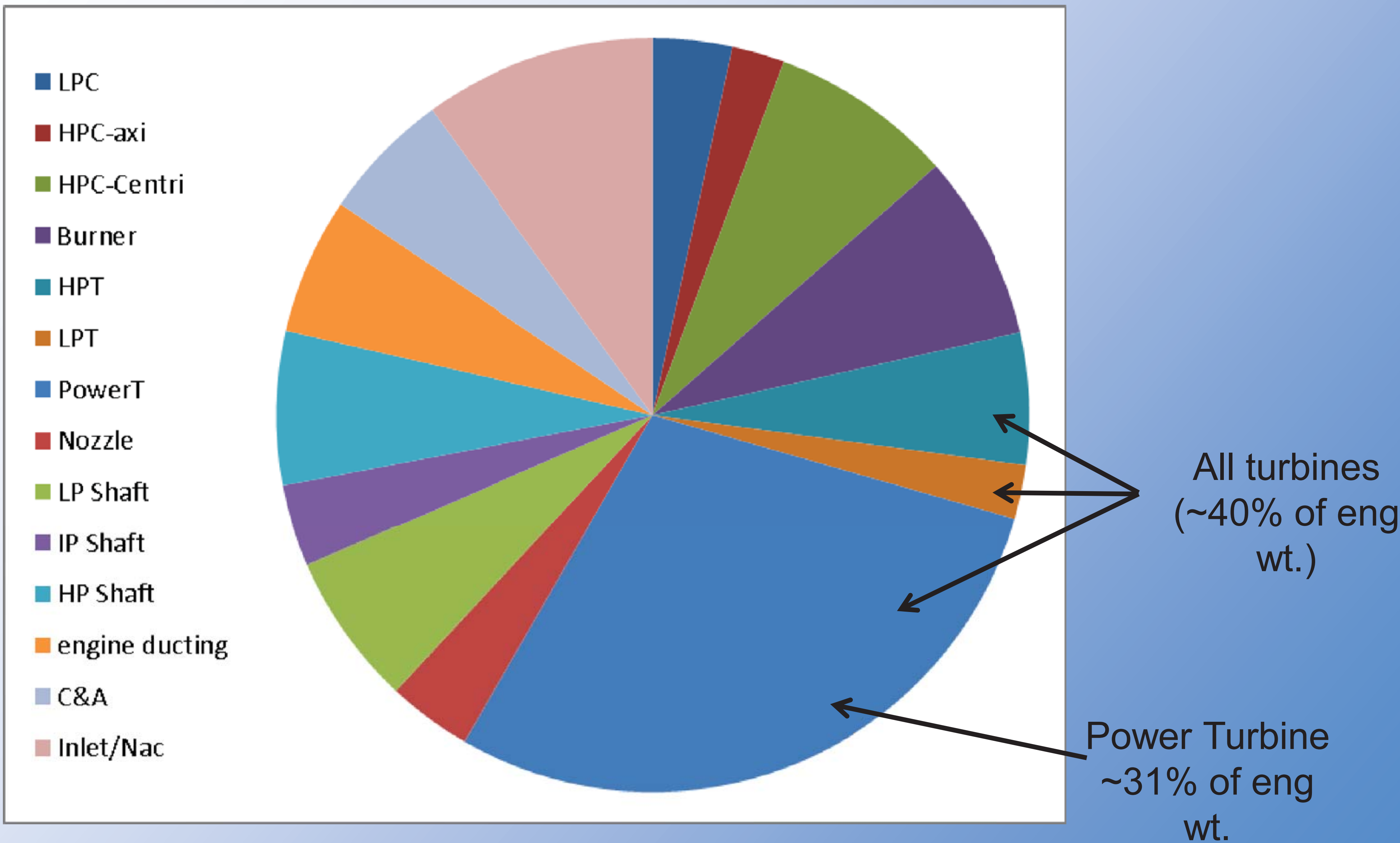
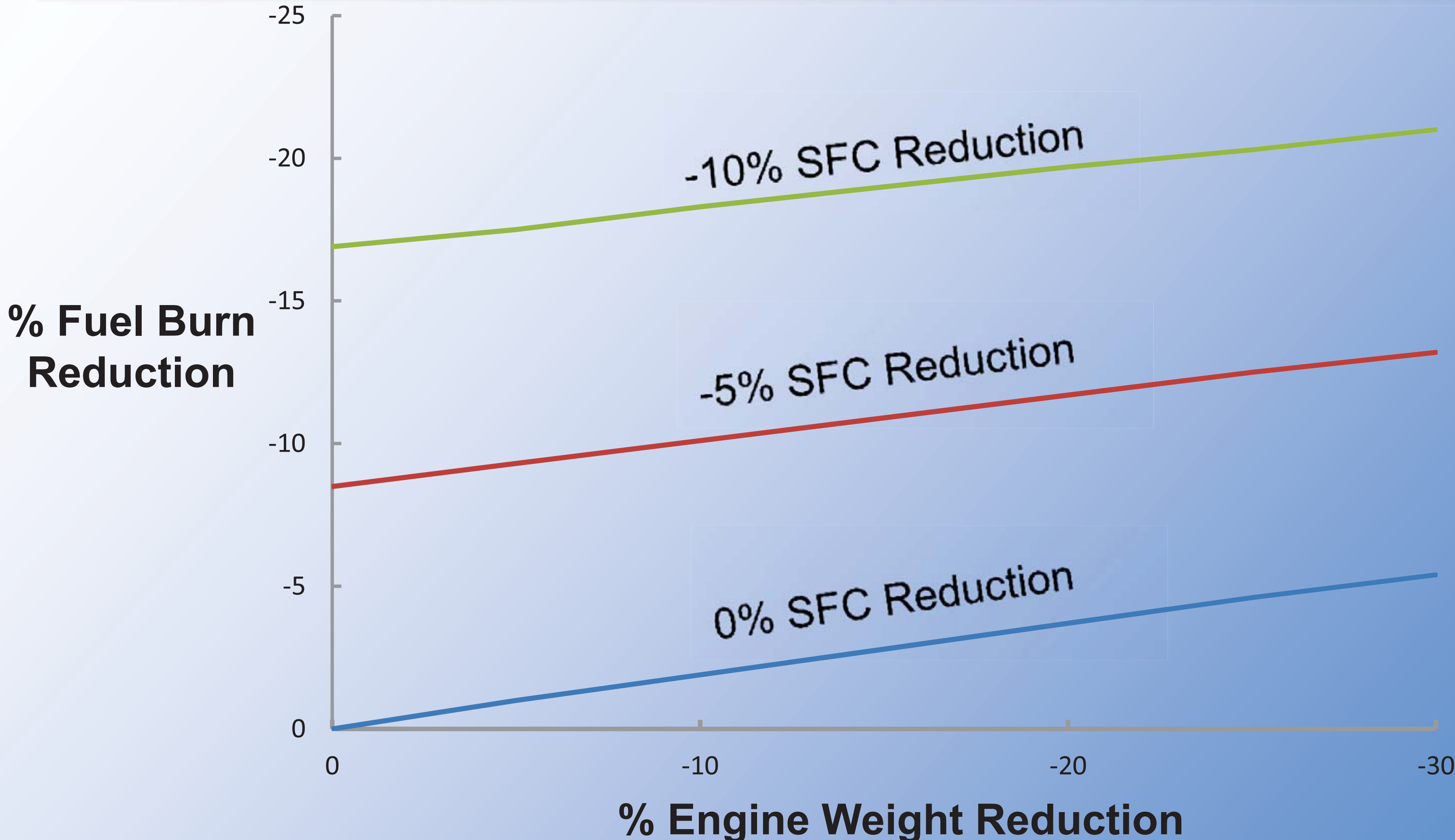
In turboshaft engines, Turbines are major weight components



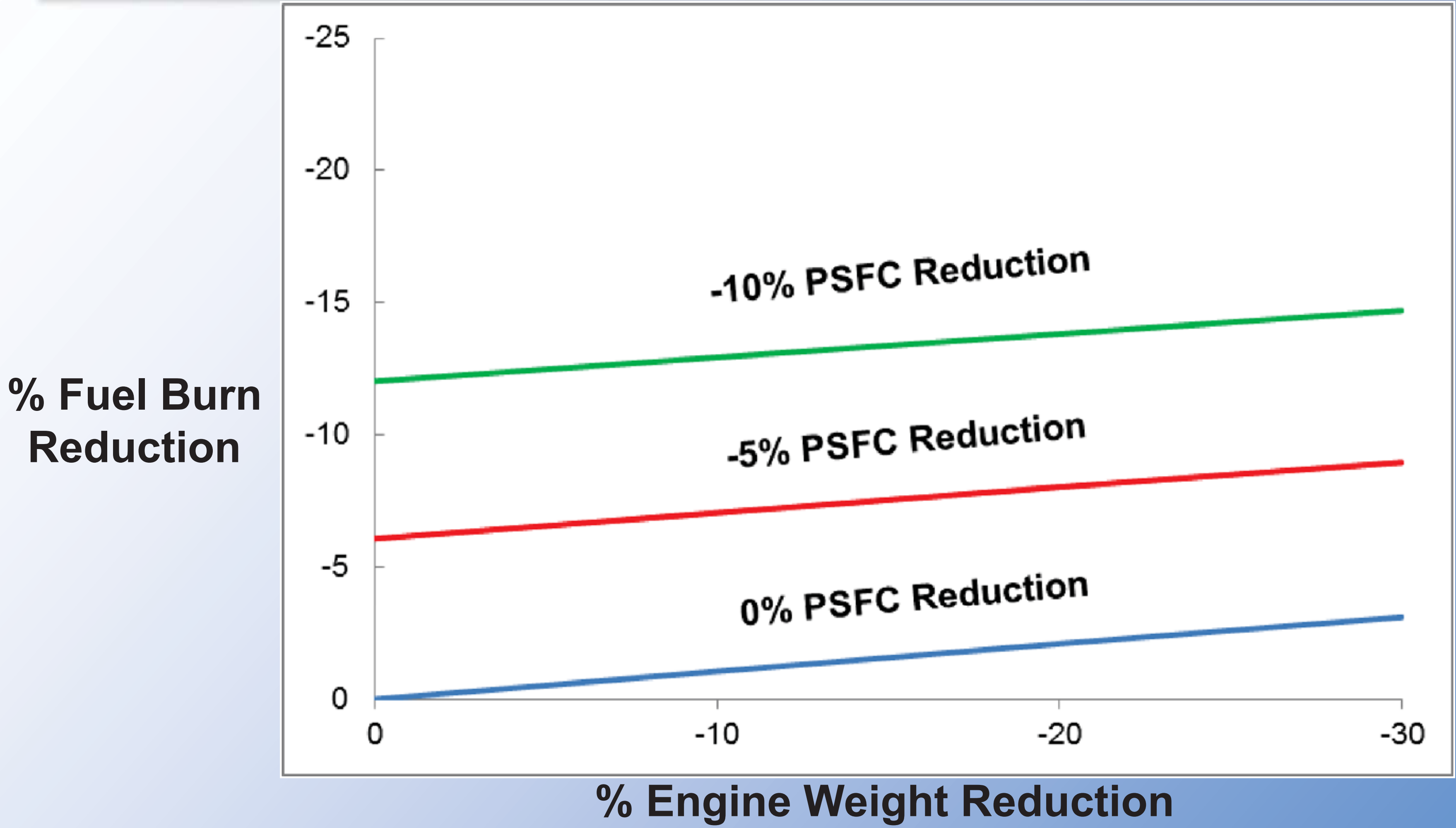
Fuel Burn Sensitivities

NASA Aeronautics Research Institute



» This was previous work for a 300 PAX aircraft
» Benefits might be slightly lower for N2A (767 class) aircraft

Fuel Burn Sensitivities



» This is for the LCTR2 baseline vehicle
» Shorter mission range reduces benefits seen from 300pax

Notional vehicle characteristics

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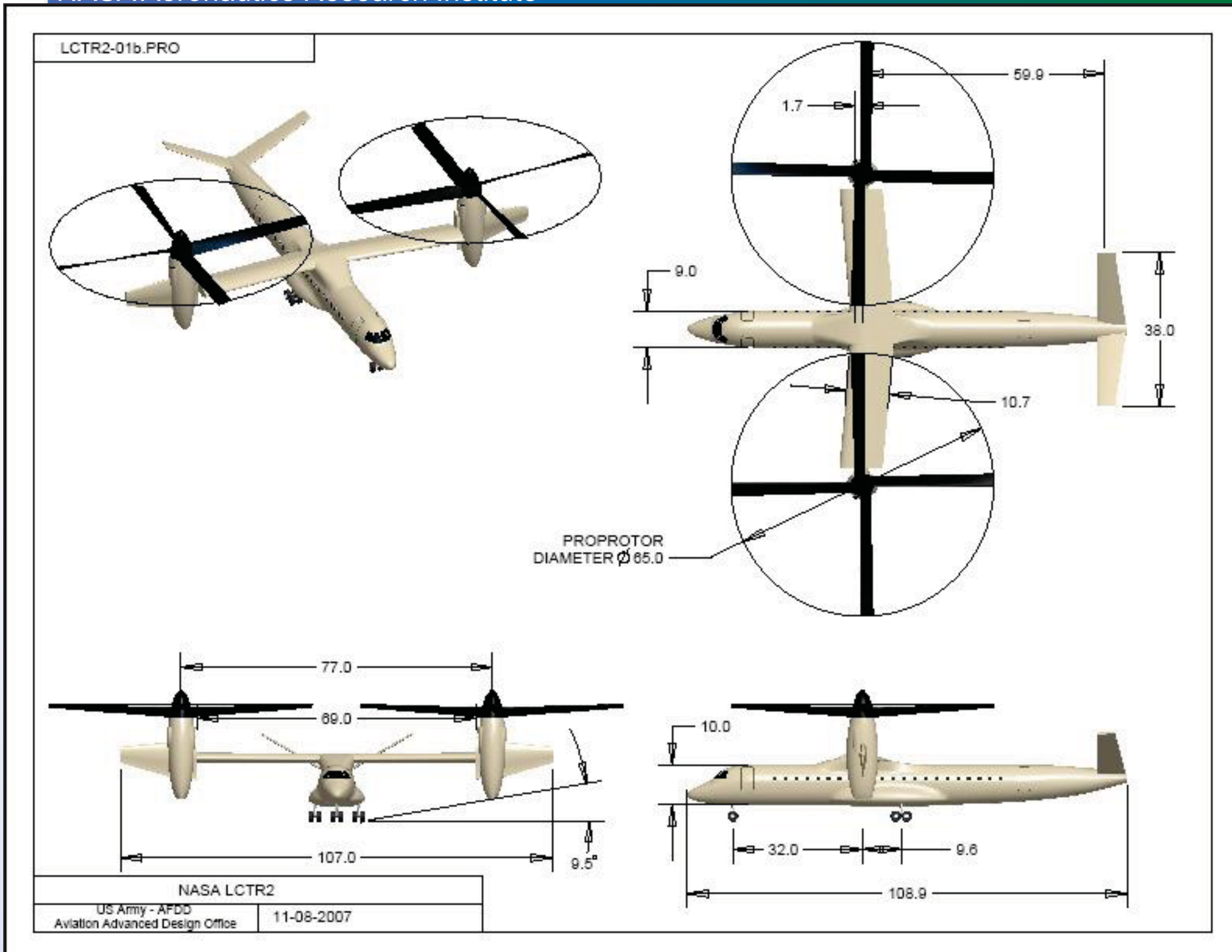


Drawing / dimensions are from previous iteration, but are representative

EIS = 2025 (2018 tech)

TOGW =89k lbm

Payload = 90 pass.

Engine = 4x5,200 HP

Fuel = 9,500 lbm

Range > 1,000nmi

Cruise > 300 knots

Cruise altitude 28k-ft

Cruise L/D ≈ 12

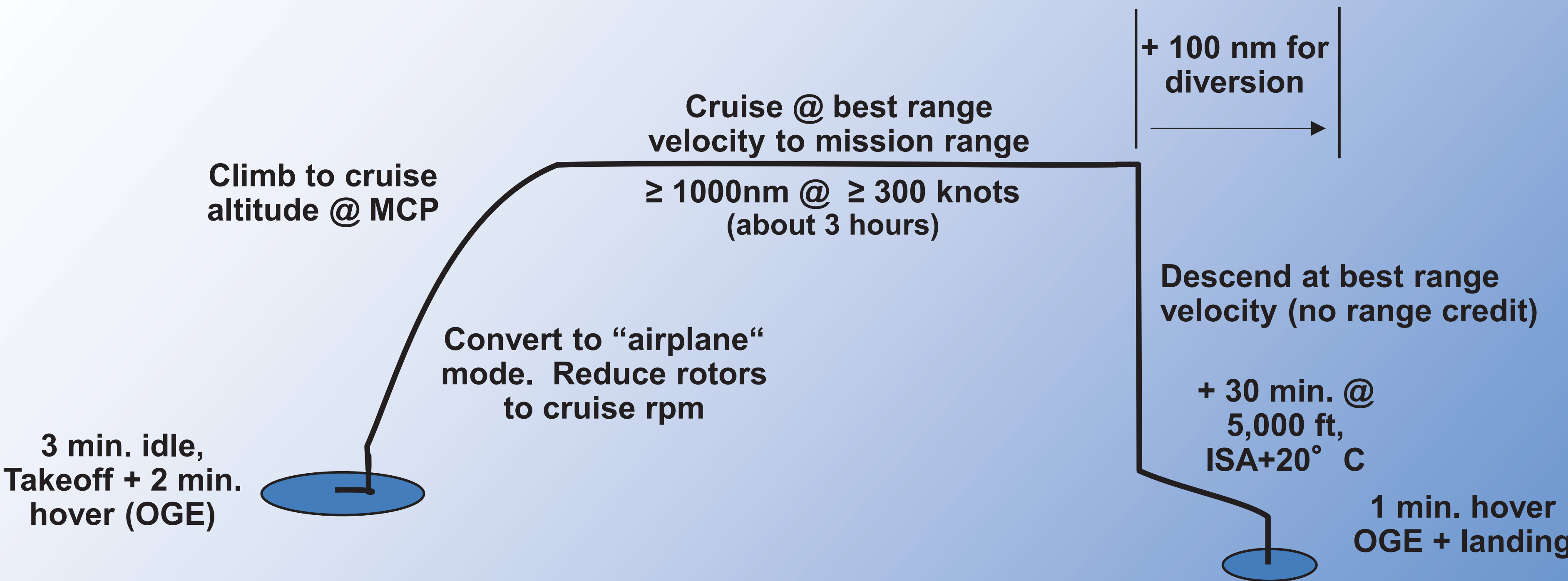
Rotor tip speed

650 fps hover

350 fps cruise

LCTR "Design" Mission Profile (similar to Regional aircraft)

NASA Aeronautics Research Institute



Mission is Climb/Cruise dominated ≈80% fuel

Modeled in NDARC — NASA Design and Analysis of Rotorcraft

Johnson, W., "NDARC, NASA Design and Analysis of Rotorcraft," NASA TP 2009-215402, December 2009